9th International Workshop on "Neutrino Telescopes"

Venice, March 6th, 2001

Global Analysis of Neutrino Oscillation Data

GLF

1. Introduction: neutrino oscillation evidence
2. The "standard" 3ν interpretation
3. 3ν oscillations: atmospheric neutrinos
4. 3ν oscillations: solar neutrinos
5. Conclusions

1. Introduction

Neutrino oscillation evidence

Two kinds of observables:

- total neutrino event rates

  $\Rightarrow$ give information on "averaged" neutrino oscillation probability $\langle P_{\alpha\beta} \rangle$

- neutrino event spectra (as a function of E, L, L/E, or t)

  $\Rightarrow$ give information on $\frac{\partial P_{\alpha\beta}}{\partial x}$ $\quad x = \left| \begin{array}{l} E \\ L \\ L/E \\ t \\ \ldots \end{array} \right.$

crucial to assess oscillations unambiguously !!!

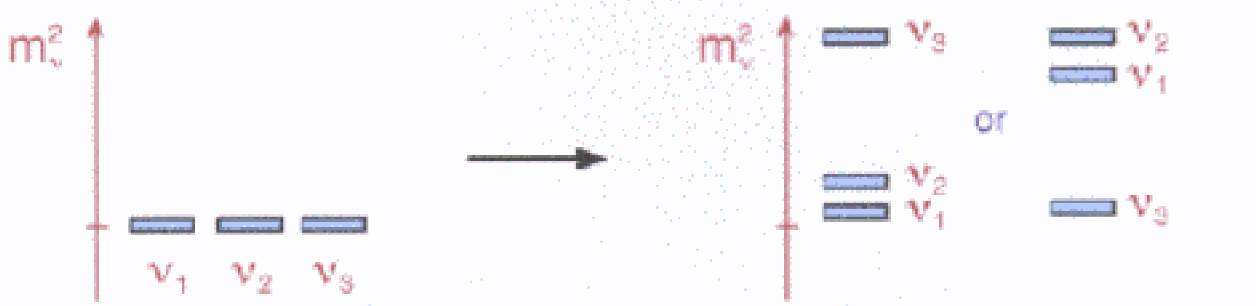
Present evidence

	total rate	spectra
LSND	$P(\nu_\mu \to \nu_e) > 0$ (controversial)	no significant info
solar	$P(\nu_e \to \nu_e) < 1$ (robust)	no significant indication for $\frac{\partial P_{ee}}{\partial(t, E, L)} \neq 0$
atmospheric	$P(\nu_\mu \to \nu_\mu) < 1$ (robust)	$\frac{\partial P_{\mu\mu}}{\partial L} \neq 0$ (very robust) $\frac{\partial P_{\mu\mu}}{\partial E} \neq 0$ (robust)

Limiting our attention to the "robust" information, we can describe it within a "standard" 3ν interpretation

2. The "standard" 3ν interpretation

The two strongest sources of evidence for neutrino oscillations (atmospheric and solar ν anomalies) can be accomodated in a "standard" framework (3ν oscillations) that requires a minimal modification of the electroweak model:



zero mass — at least two nonzero masses

$$U = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \longrightarrow U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$$

no mixing — at least two nonzero mixing angles (ω, ψ)

We assume then

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix} = U(\theta_{ij}, \delta_{CP}) \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}$$

with in the following

$$\omega = \theta_{12}$$
$$\phi = \theta_{13}$$
$$\psi = \theta_{23}$$

status and prospects of such interpretative framework will be discussed in this talk

Parameters probed by oscillations

1. $\delta m^2 \stackrel{\text{def}}{=} m_2^2 - m_1^2$ — $\delta m^2 \ll m^2$ from phenomenology

with

2. $m^2 \stackrel{\text{def}}{=} |m_3^2 - m_{1,2}^2|$ — $\pm m^2$ both scenarios allowed

3. $\omega = \theta_{12} \in [0,\pi/2]$

4. $\varphi = \theta_{13} \in [0,\pi/2]$

5. $\psi = \theta_{23} \in [0,\pi/2]$

6. $\delta = \delta_{CP} \in [0,\pi]$

MINIREVIEW

PARAMETER	STATUS	PROSPECTS
m^2	$\sim 3 \times 10^{-3}$ eV^2 within a factor of ~ 2	Good. It will be better and better determined by atm. and LBL expts.
δm^2	$\neq 0$ but multiple ranges allowed (MSW,QV)	Selection of one of the different solutions will take years
ψ	$s_\psi^2 \sim 1/2$ within a factor of ~ 2	as for m^2
ω	$\neq 0$ but multiple ranges allowed (MSW,QV)	as for δm^2
φ	$s_\varphi^2 \lesssim$ few % (CHOOZ) but no reason for $s_\varphi^2 = 0$!	Its determination will be one of the major challenges for future reactor, atmospheric and LBL experiments.
δ	unconstrained. Effects suppressed by $\delta m^2/m^2$	very bad before ν factories

Graphical representation of parameter space

$\delta m^2 \ll m^2$ implies that:

① δ_{CP} ~ unobservable effects doubly suppressed by $\left\{ \begin{array}{l} \delta m^2/m^2 \to 0 \\ \sin^2\varphi \to 0 \end{array} \right.$

we will assume U real. Difficult to prove $\delta_{CP} \neq 0$ in future exps.

② Solar ν (up to terms of the order $\delta m^2/m^2$ the parameter space is spanned only by three variables:

$(\delta m^2, \omega, \phi) \Leftrightarrow (\delta m^2, U_{e1}^2, U_{e2}^2, U_{e3}^2)$ with $U_{e1}^2 + U_{e2}^2 + U_{e3}^2 = 1$ (unitarity)

or equivalently

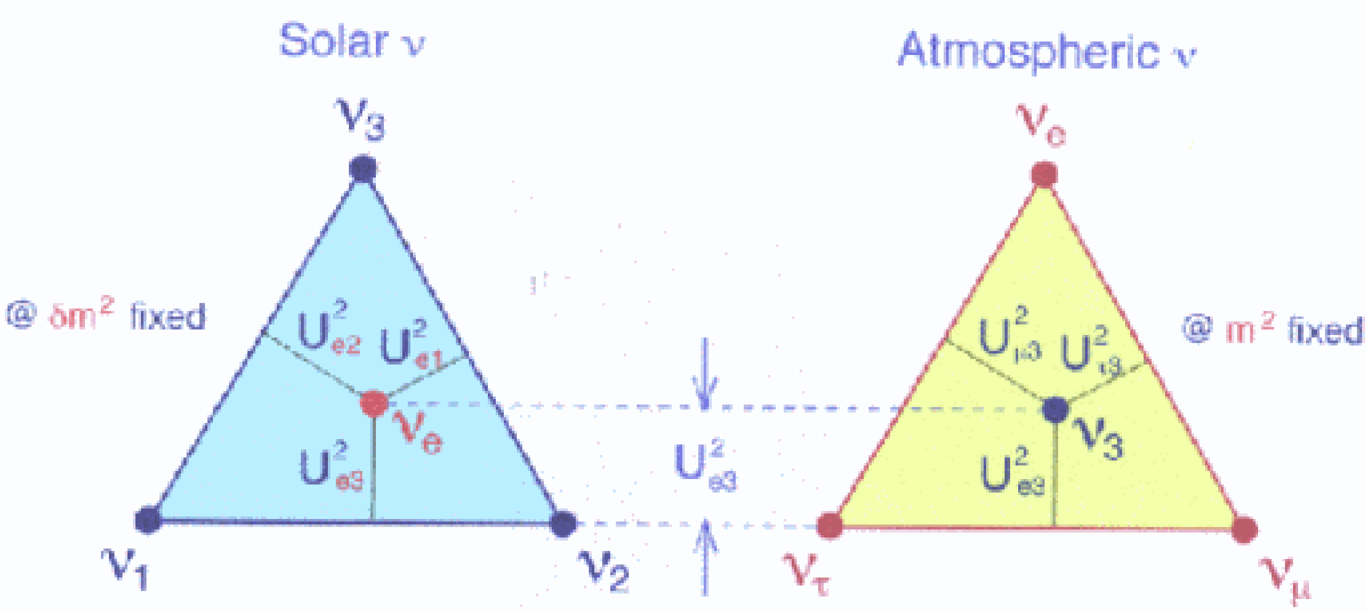
Relevant the mass composition of ν_e: $\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$

③ Atmospheric ν (or, in general, terrestrial ν): up to terms of the order $\delta m^2/m^2$ the parameter space is spanned by only three variables:

$(m^2, \psi, \phi) \Leftrightarrow (m^2, U_{e3}^2, U_{\mu 3}^2, U_{\tau 3}^2)$ with $U_{e3}^2 + U_{\mu 3}^2 + U_{\tau 3}^2 = 1$ (unitarity)

or equivalently

Relevant the flavour composition of ν_3: $\nu_3 = U_{e3}\nu_e + U_{\mu 3}\nu_\mu + U_{\tau 3}\nu_\tau$



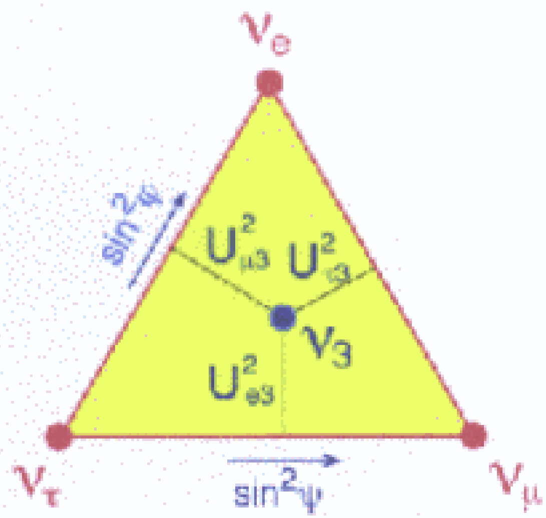
U_{e3}^2 probed by solar AND atmospheric ν experiments

3. 3ν oscillations: atmospheric neutrinos

$\nu_3 = U_{e3}\,\nu_e + U_{\mu 3}\,\nu_\mu + U_{\tau 3}\,\nu_\tau =$

$= s_\phi \nu_e + c_\phi (s_\psi \nu_\mu + c_\psi \nu_\tau)$

@ m^2 fixed



being

$U^2_{e3} = s^2_\phi$

$U^2_{\mu 3} = c^2_\phi\, s^2_\psi$

$U^2_{\tau 3} = c^2_\phi\, c^2_\psi$

The analysis includes:

- The latest (December 2000: 79.5 kTy) SK data:

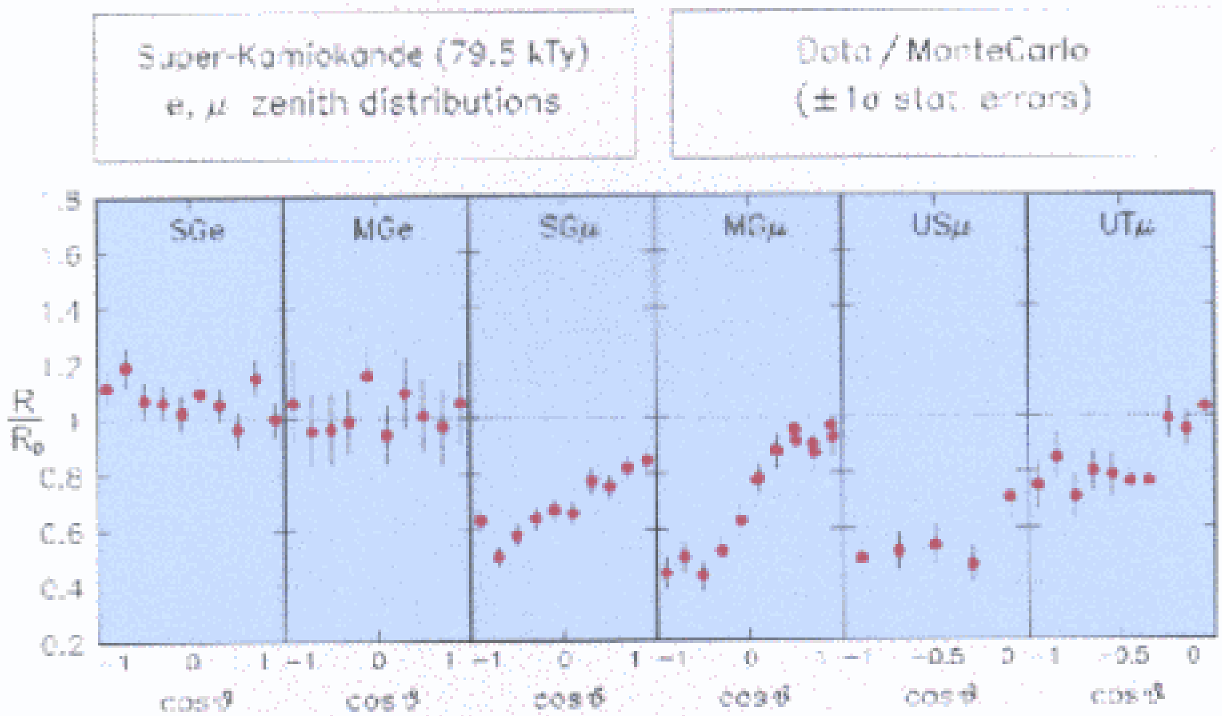
  10 SubGeV e-like bins
  10 SubGeV μ-like bins
  10 MultiGeV e-like bins
  10 MultiGeV μ-like bins
  5 stopping upgoing μ bins
  10 through-going μ bins

- The latest (1999) CHOOZ total rate

  1 data point

SK zenithal distributions (Dec. 2000 data: 79.5 kTy)

(normalized to NO OSCILLATION in each bin)



⇑ electrons ⇑ muons ⇑ Upgoing-μ

Comments:

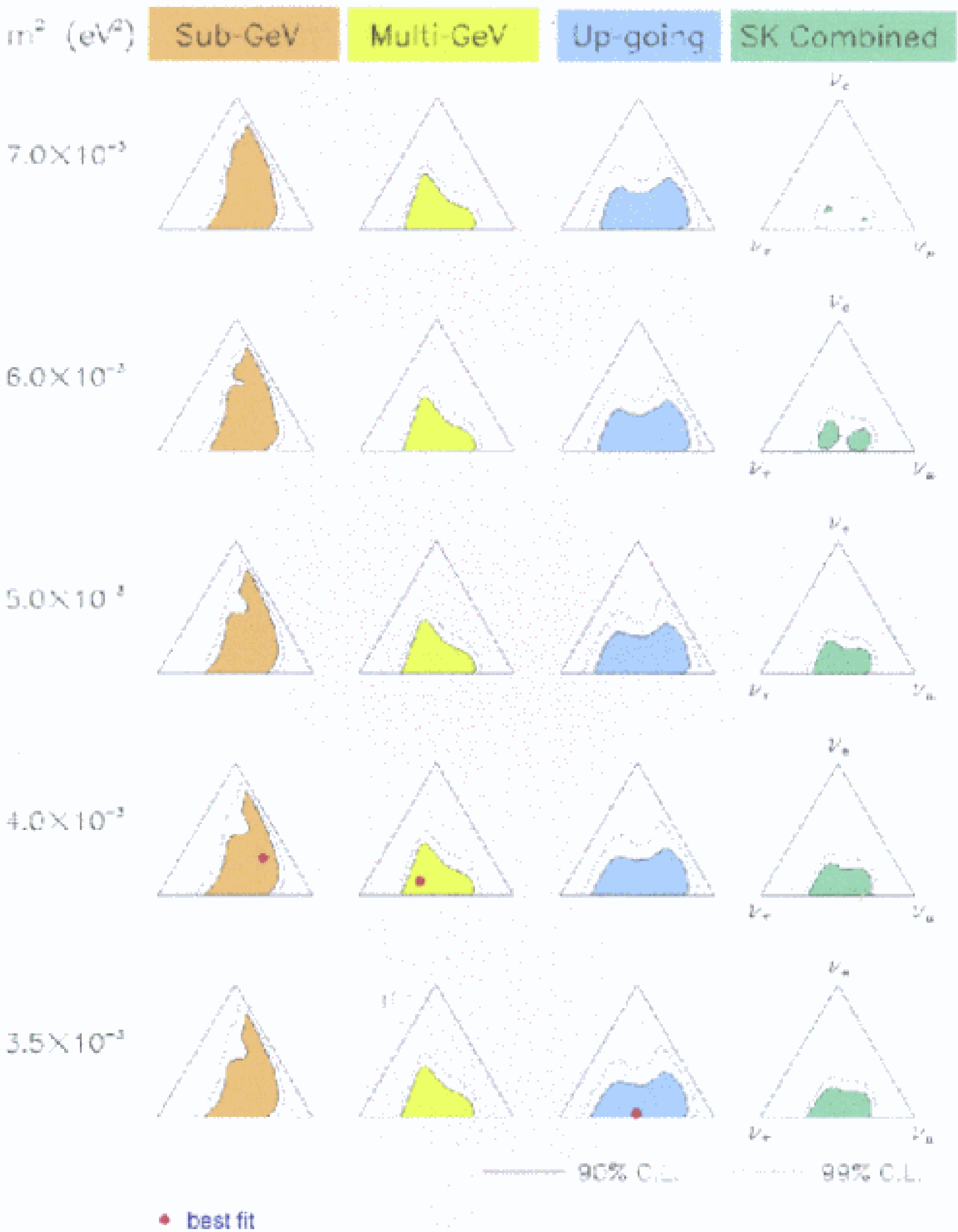
- electrons: no significant deviation from a flat shape (any excess disappeared)
- up-muons: UTμ possibly affected by fluctuations (shape not statistically stable yet)

CHOOZ

$$\frac{R_{exp}}{R_{theo}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)}$$

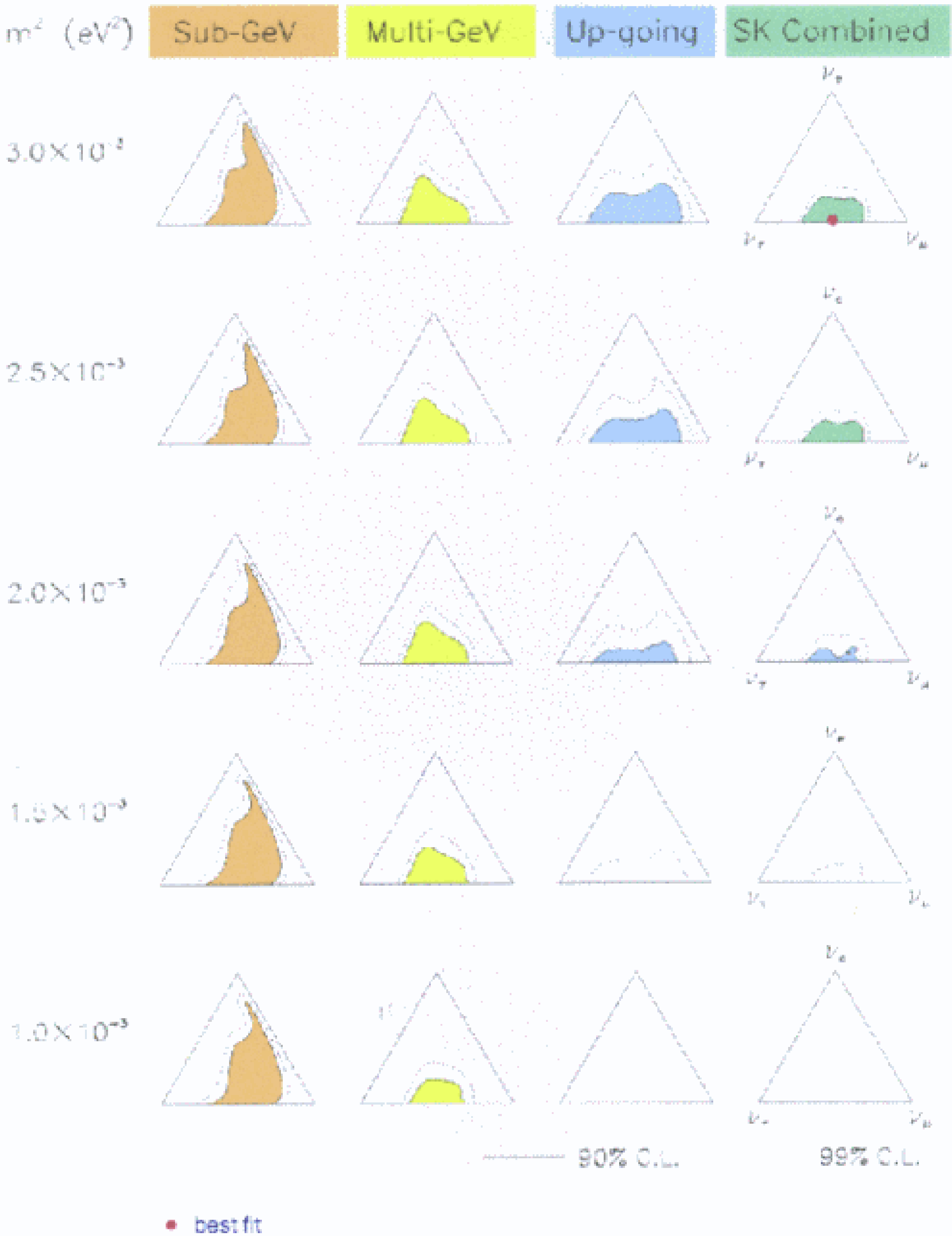
Allowed regions in a three-flavour approach

(Dec. 2000 SK data: 79.5 kTy)



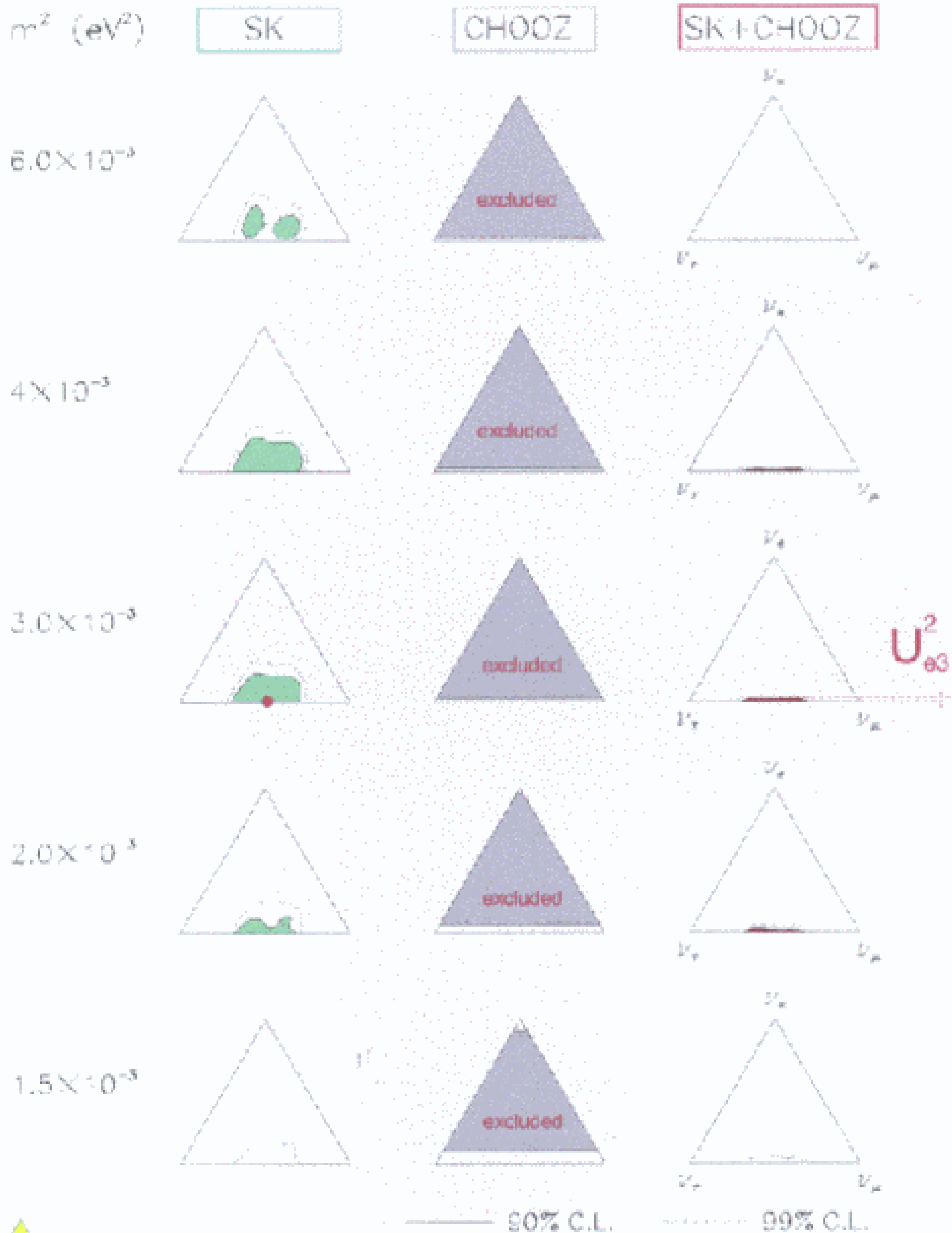
Allowed regions in a three-flavour approach

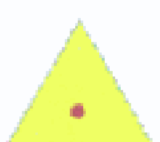
(Dec. 2000 SK data: 79.5 kTy)



Combining Superkamiokande and CHOOZ

(Dec. 2000 SK data: 79.5 kTy)

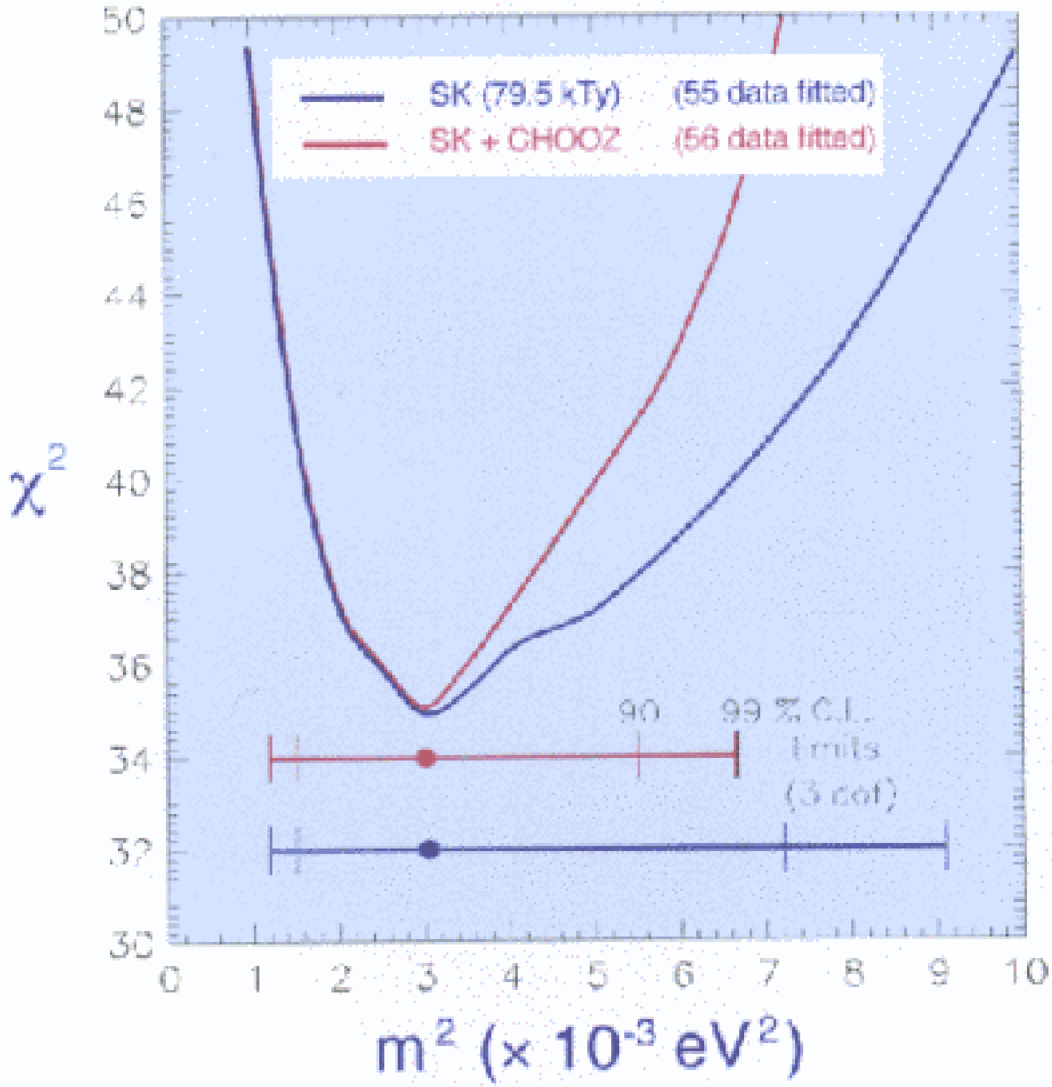




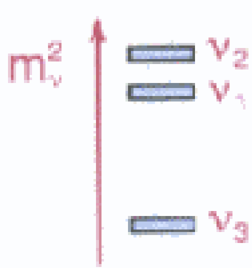
scenarios with large ν_e mixing excluded, e.g. threefold maximal mixing

Bounds on m^2 for unconstrained 3ν mixing

(79.5 kTy SK data)



- best-fit @ $m^2 = 3.0 \times 10^{-3}$ eV^2

- 

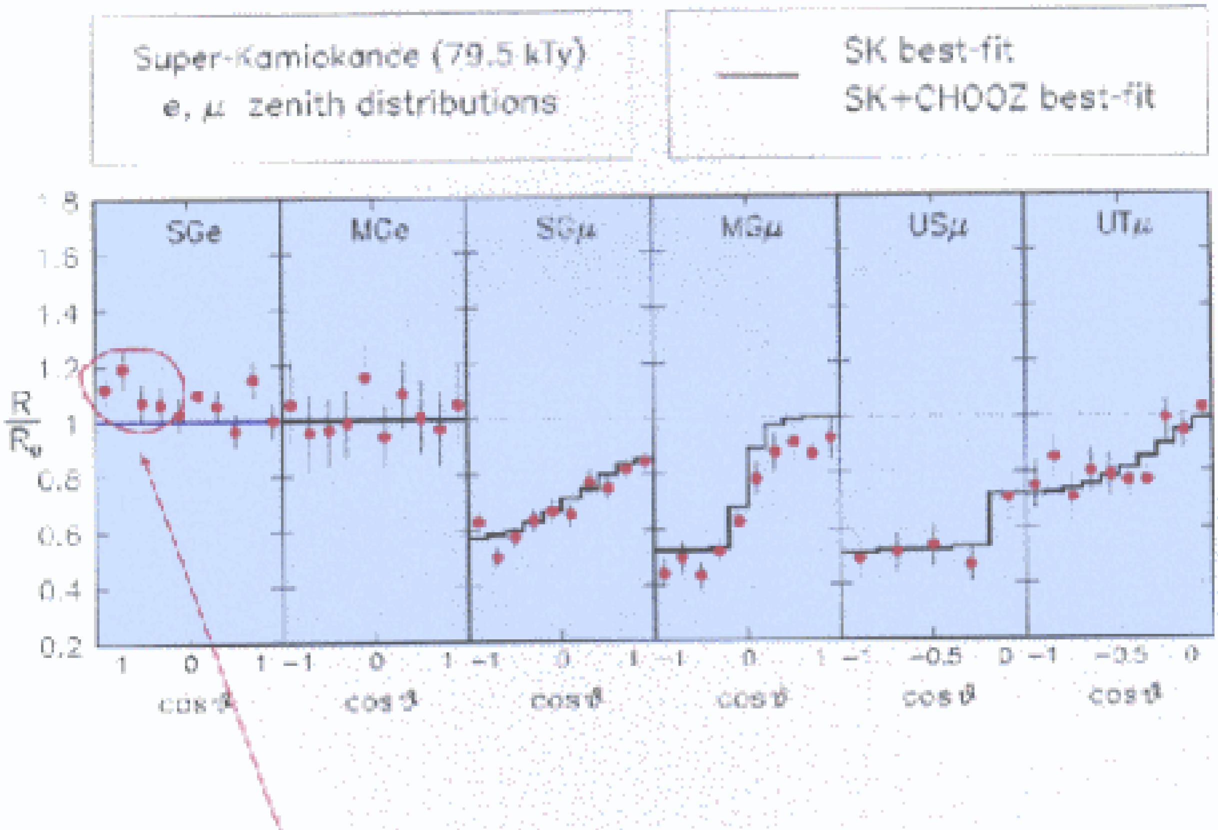
The fit for $-m^2$ is very similar: SK does not distinguish the two cases. In the limit of pure $\nu_\mu \leftrightarrow \nu_\tau$, i.e. $\varphi = 0$,

$$P_{osc}(m^2) = P^{vac}_{osc}(m^2) = P^{vac}_{osc}(-m^2)$$

For small φ there are small differences due to matter effects, unobserved at present

Best-fit distributions

SK alone
SK+CHOOZ
> U^2_{e3} consistent with zero (pure $\nu_\mu \leftrightarrow \nu_\tau$ favoured)



Possible deviations from flat due to $\nu_\mu \leftrightarrow \nu_e$ oscillations are typically smaller than these

Sources of possible deviations:

- $\varphi \neq 0$
- subleading δm^2 effects if $\delta m^2 \sim 10^{-4}$ eV^2

Both effects may alter the SGeV/MGeV e distributions: much higher SK statistics needed to see such effects !!

Status of (m^2, ψ, φ) constraints

① $m^2 \simeq 3 \times 10^{-3}$ eV^2 within a factor of 2 ($1.5 \div 6.0 \times 10^{-3}$ eV^2)

② $s^2_\psi \simeq 0.5 \pm 0.17$

③ $s^2_\varphi \lesssim$ few percent

Prospects

- SK will steadily narrow the range of (m^2, s^2_ψ) until systematics will dominate. Next major improvement will be provided by LBL experiments.

- Signals of $s^2_\varphi \neq 0$ are, and will be, more difficult to observe:

SK ⇒ Typical signals of $s^2_\varphi \neq 0$ are smaller than present 1σ statistical uncertainties. To establish them at the 2σ level, more than 4 years are required....(much more if systematics are included ...)

LBL ⇒ Signals of $s^2_\varphi \neq 0$ should be searched in the $\nu_\mu \leftrightarrow \nu_e$ channel, (with $P_{e\mu} \propto s^2_\varphi$). However, CHOOZ implies that $S/B \lesssim 1$ in LBL. So, the e-flavor background should be known precisely. This is difficult but important: $\varphi \neq 0$ is the only chance to observe MSW effect with terrestrial exps. (apart from the "exotic" $\nu_\mu \leftrightarrow \nu_s$ case)

ν factories ⇒ Of course, they may provide the real option to observe $s^2_\varphi \neq 0$ in a "relatively far" future

reactors ⇒ Next logical step to increase the sensitivity to s^2_φ is to place a near detector. There is a proposal of Krasnoyarsk.

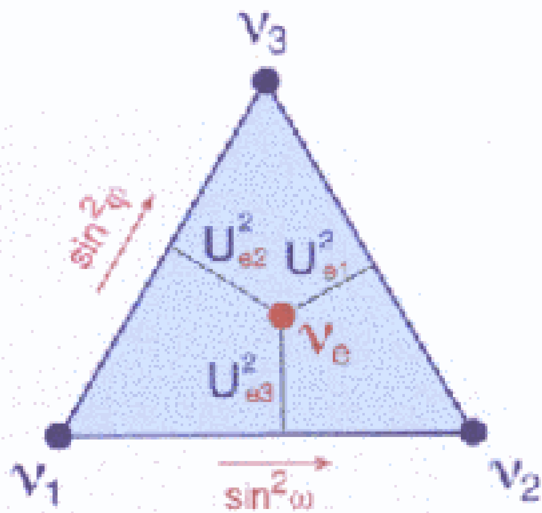
4. 3ν oscillations: solar neutrinos

$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3$$
$$= s_\phi \nu_3 + c_\phi (s_\omega \nu_1 + c_\omega \nu_2)$$

being

$$U_{e3}^2 = s_\phi^2$$
$$U_{e2}^2 = c_\phi^2\, c_\omega^2$$
$$U_{e1}^2 = c_\phi^2\, s_\omega^2$$

@ δm² fixed

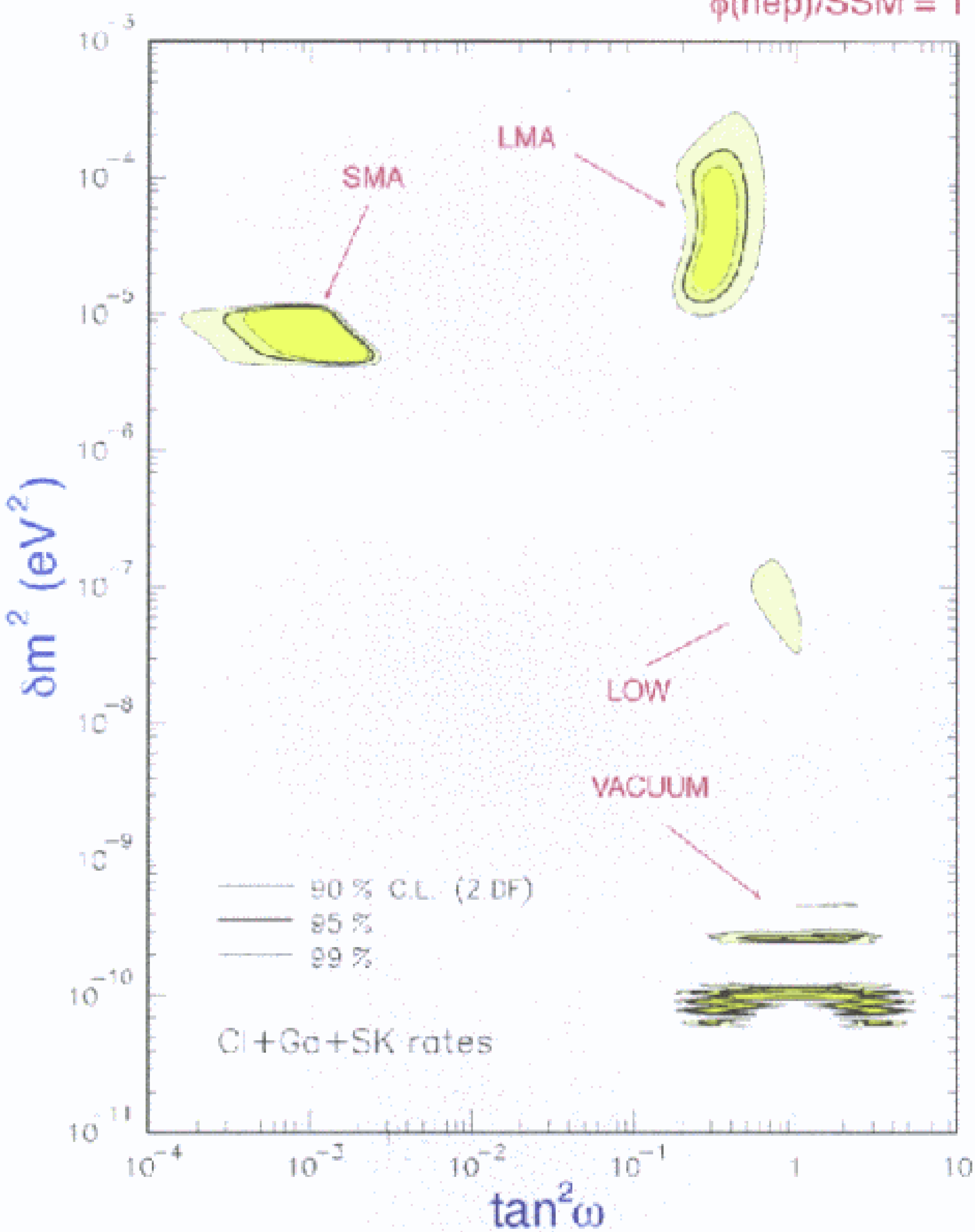


The analysis includes:

- 4 total rates: Cl = Homestake
  Ga = GALLEX+SAGE
  SK = SuperKamiokande (data presented Dec., 2000)
- 18 SK energy bins (-1 free renormalization factor)
- day-night effect from SK including separately Sp(D) & Sp(N)

In the following we will assume: SSM = BP 2000
φ(hep) = SSM value

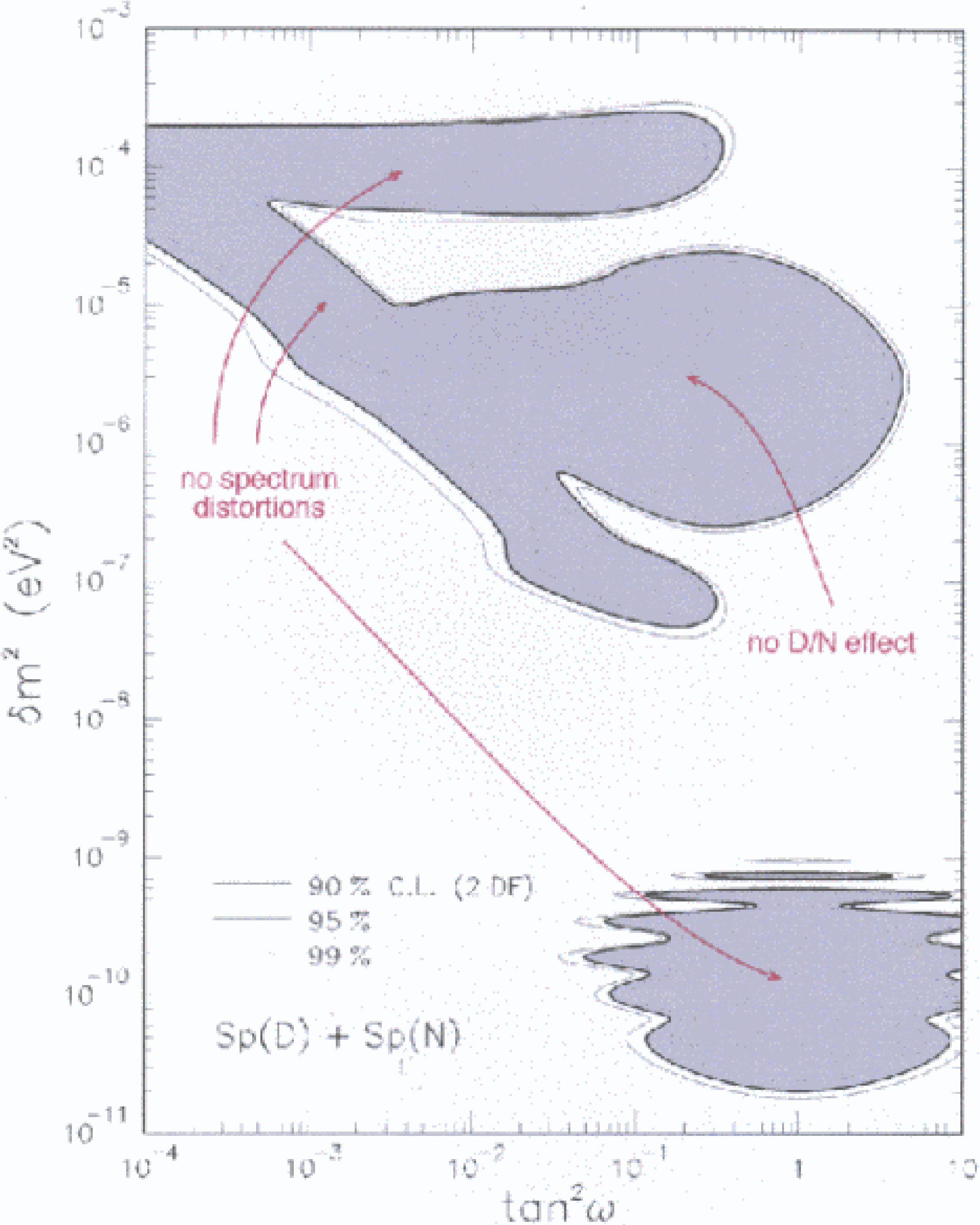
2ν oscillations (φ = 0): total rates



SMA: $\chi^2 \sim 0.25$ best fit (2 dof)
VACUUM: $\chi^2 \sim 0.26$
LMA: $\chi^2 \sim 3.55$
LOW: $\chi^2 \sim 8.05$

2ν oscillations (φ = 0): SK spectrum

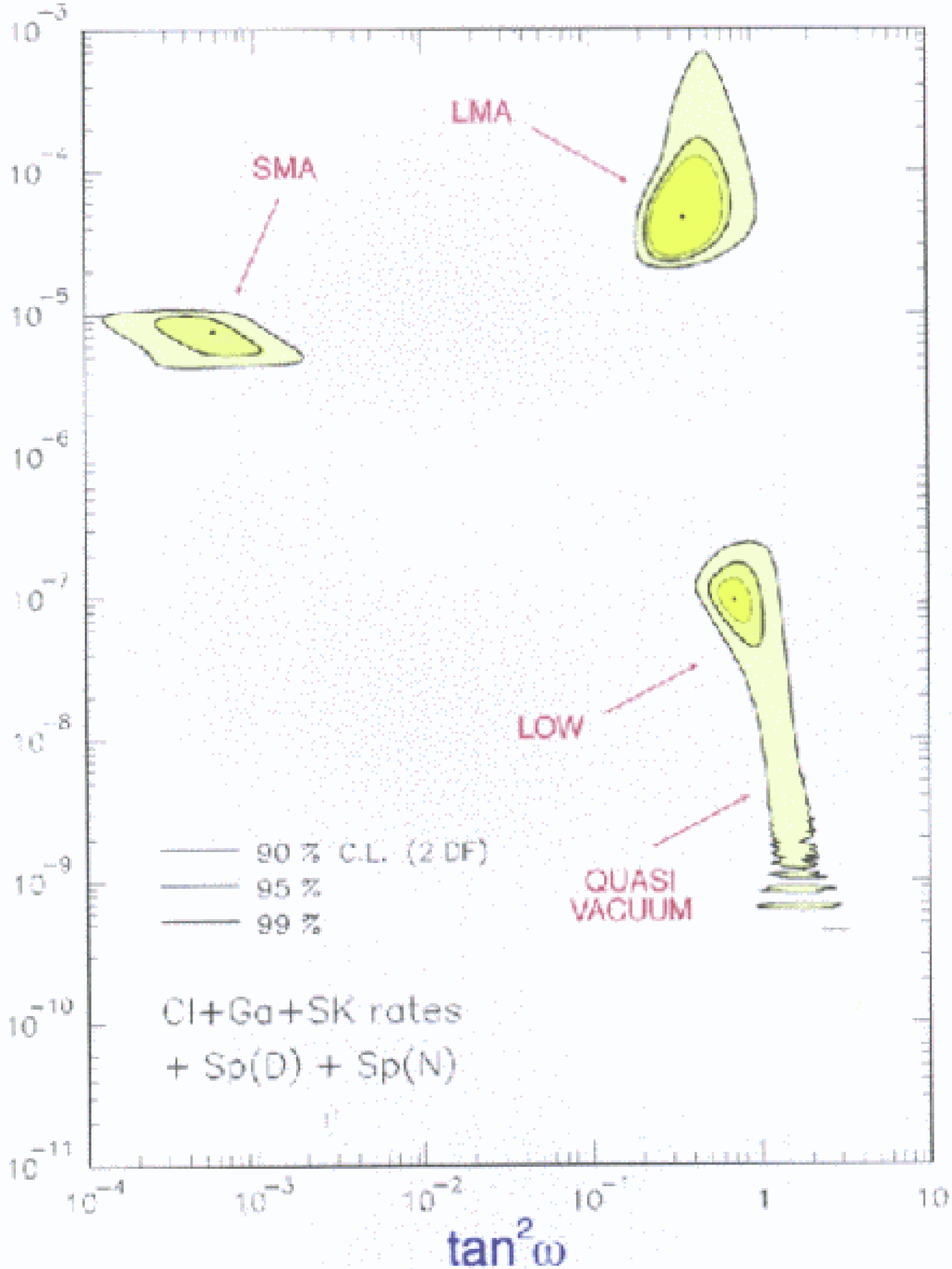
regions excluded by Sp(D) + Sp(N) (hep/SSM=1)



Comment: • Poor overlap between regions allowed by spectrum and by rates (see the previous figure)

2ν oscillations ($\varphi = 0$)

total rates and SK spectrum ($N_{dof} = 36$)



LMA: $\chi^2 \sim 35.1$

LOW: $\chi^2 \sim 39.0$

SMA: $\chi^2 \sim 40.8$

More spectral data needed to prefer or to exclude one of the solutions

Towards a 3ν analysis

2ν		3ν
$(\delta m^2, \omega)$	$\xrightarrow[m^2 \to \infty]{}$	$(\delta m^2, \omega, \varphi)$
$P_{2\nu}(\nu_e \to \nu_e)$	$\xrightarrow[m^2 \to \infty]{}$	$P_{3\nu} = c_\varphi^4 P_{2\nu}\Big\vert_{N_e = c_\varphi^2 N_e} + s_\varphi^4$

φ small (CHOOZ) implies that $P_{3\nu} \sim P_{2\nu}$, so why we study the case of unconstrained φ ?

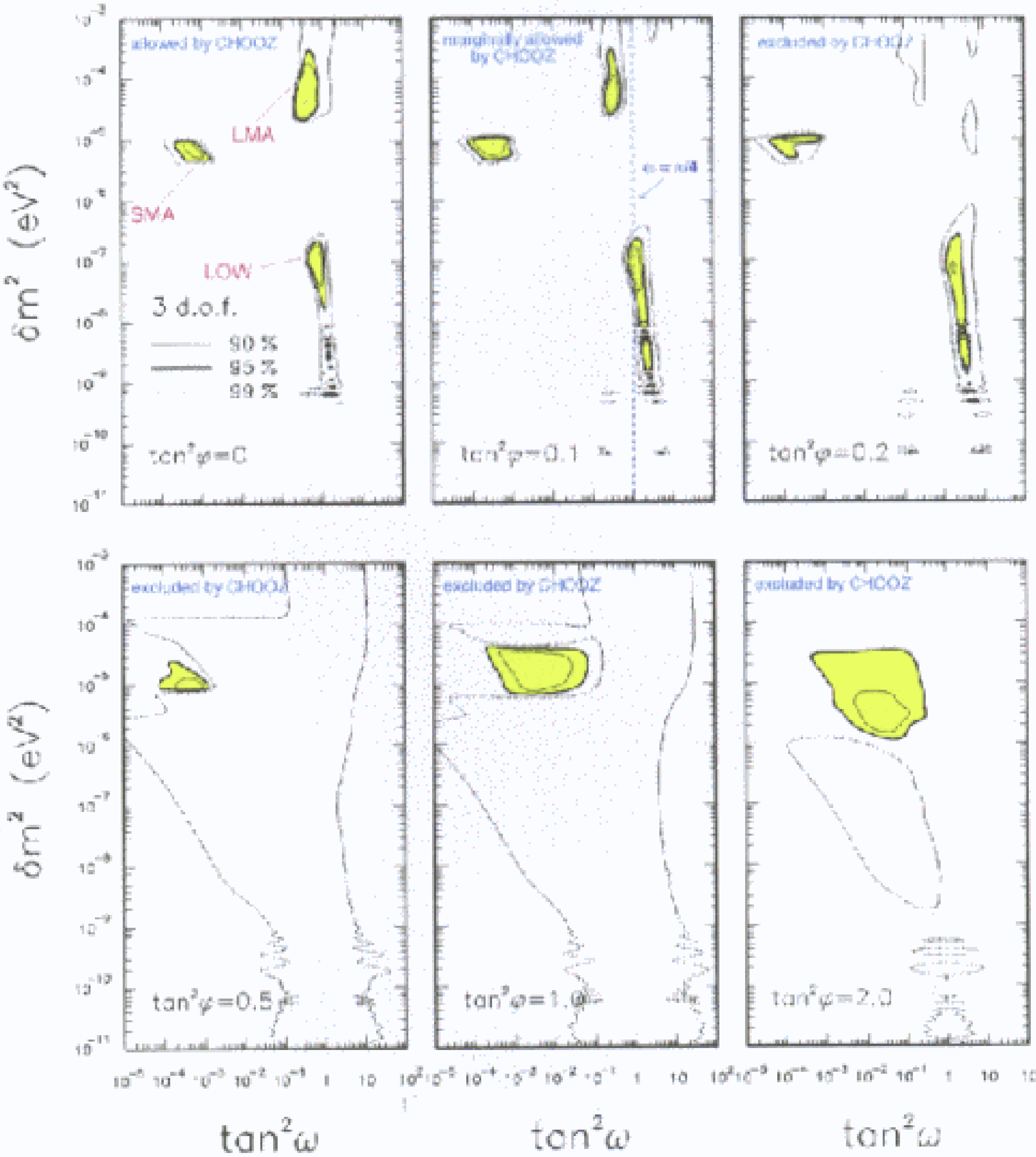
Two reasons:

- Investigate if solar ν data alone (without CHOOZ) prefer small φ, in the same way as atmospheric data alone
- Study the behaviour of the usual 2ν solutions, in particular SMA, LMA and LOW, under small φ perturbations

In the following ϕ(hep) = SSM value is assumed.

3ν solutions (hep/SSM = 1)

total rates with constraints from Sp(D)+Sp(N)

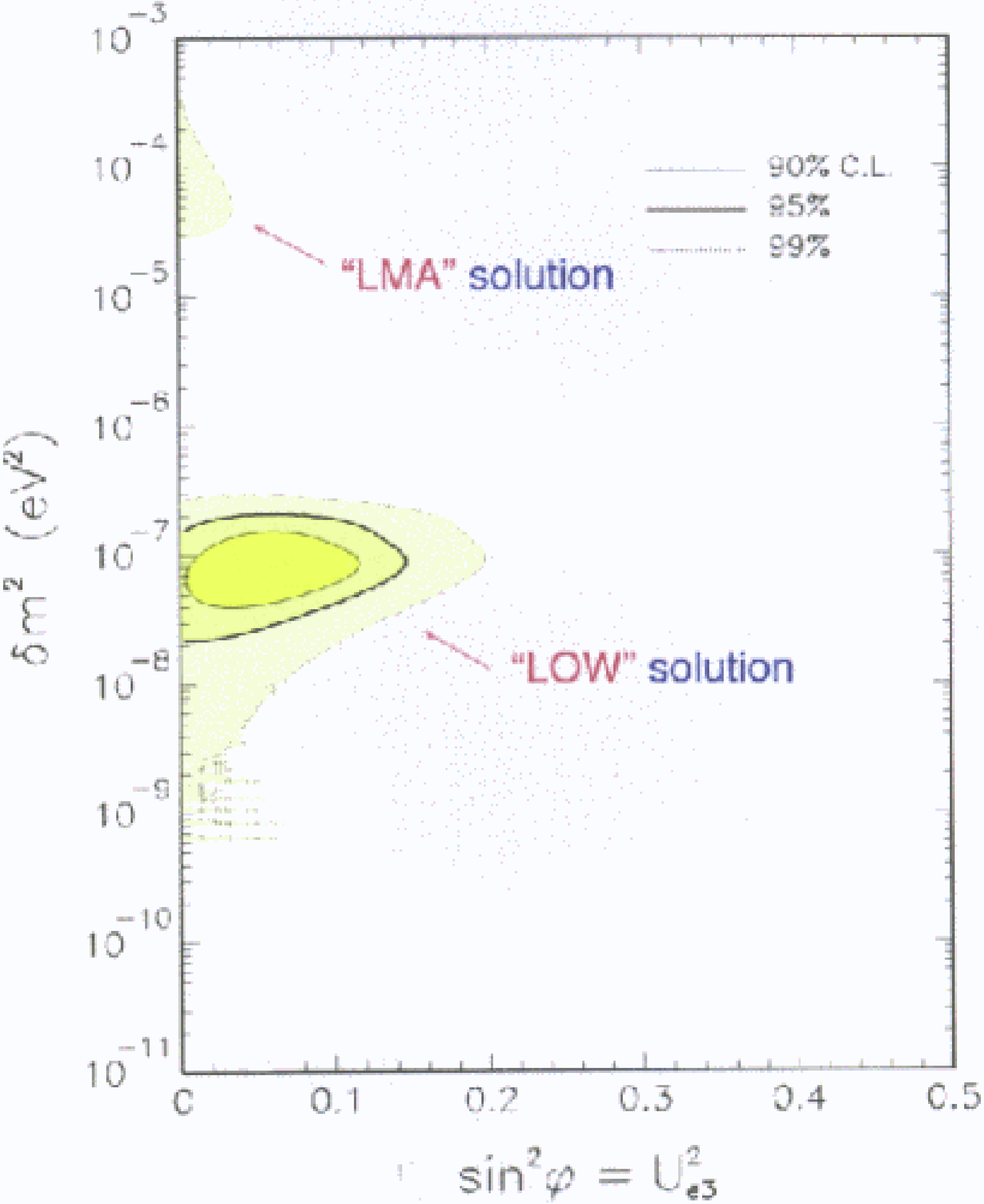


Comments:

- Still loose bounds ($s_\varphi^2 < 0.7$) with $s_\varphi^2 \sim 0.1$ preferred
- For small φ, maximal mixing solutions are allowed ! The LOW solution migrates toward $\omega = \pi/4$, and one can even have solutions for $\omega = \pi/4 + \varepsilon$ (completely missed if one uses $\sin^2 2\omega$ as variable)

3ν solutions @ maximal mixing

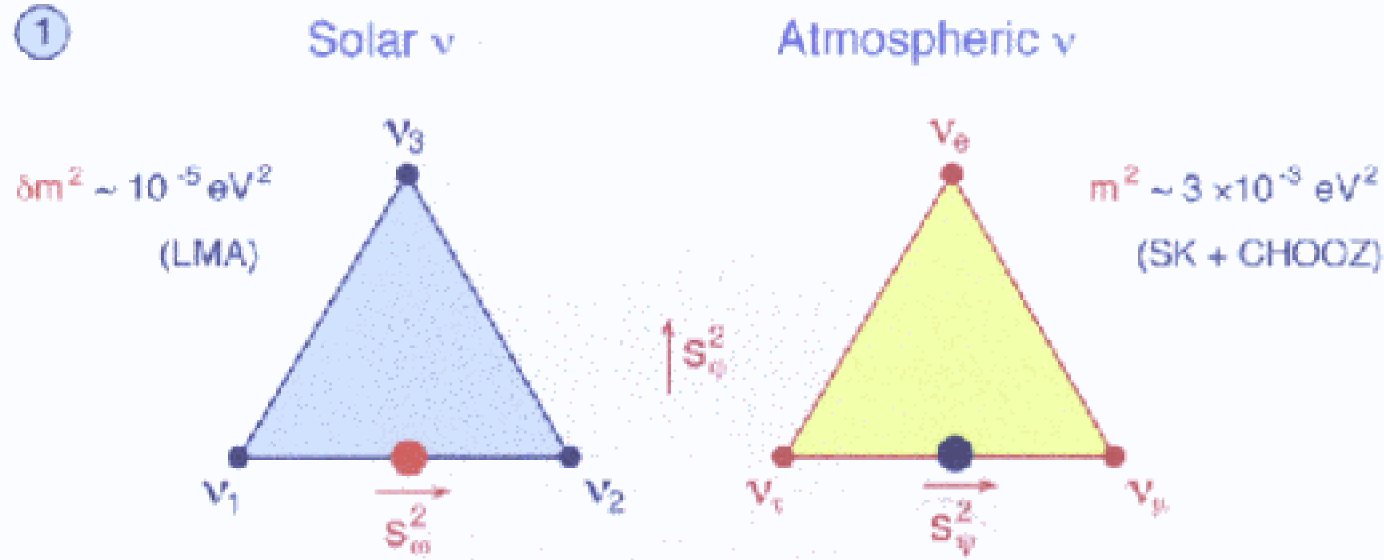
Comparison between "LOW" and "LMA" solutions assuming maximal $\nu_{1,2}$ mixing: $U^2_{e1} = U^2_{e2}$ ($\omega = \pi/4$)



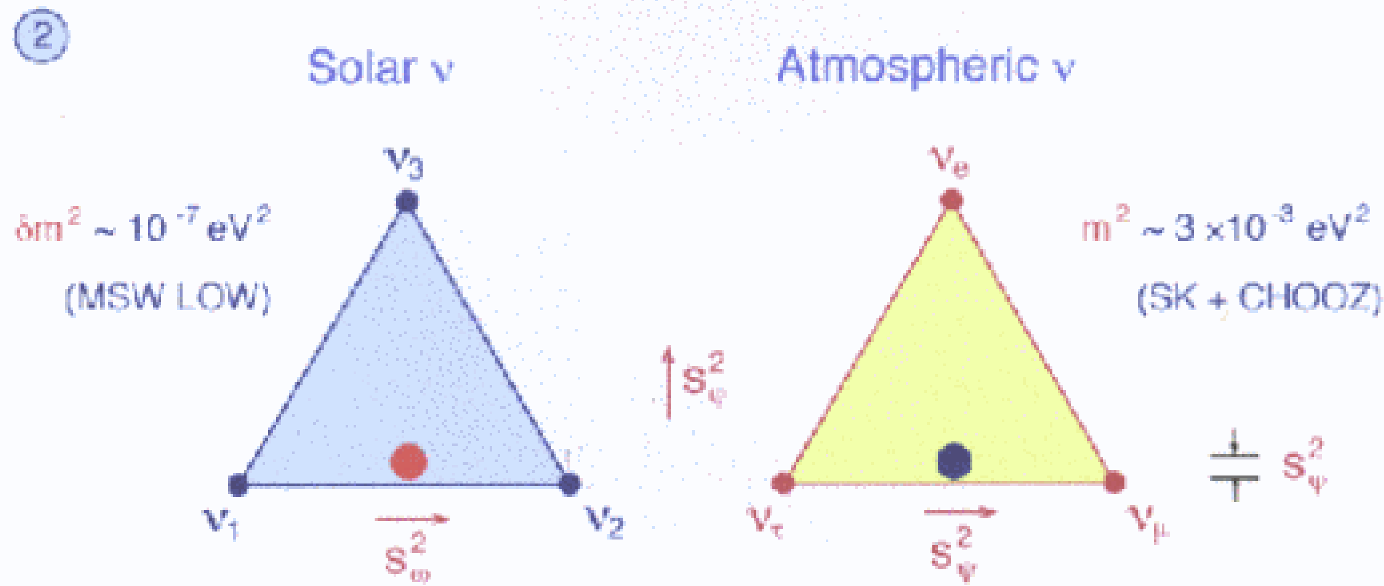
At maximal (ν_1, ν_2) mixing:

- the LOW solution is enhanced for $U^2_{e3} \sim 0.05$
- $\chi^2_{min} = 39.9$ (for $\delta m^2 = 7.8 \times 10^{-8}$ eV ^{2}and $\sin^2\varphi \sim 6 \times 10^{-2}$)

The previous result is interesting for model building: bimaximal mixing can be reached not only with the LMA solution, but also with the LOW solution, but as a bimaximal mixing at small φ:

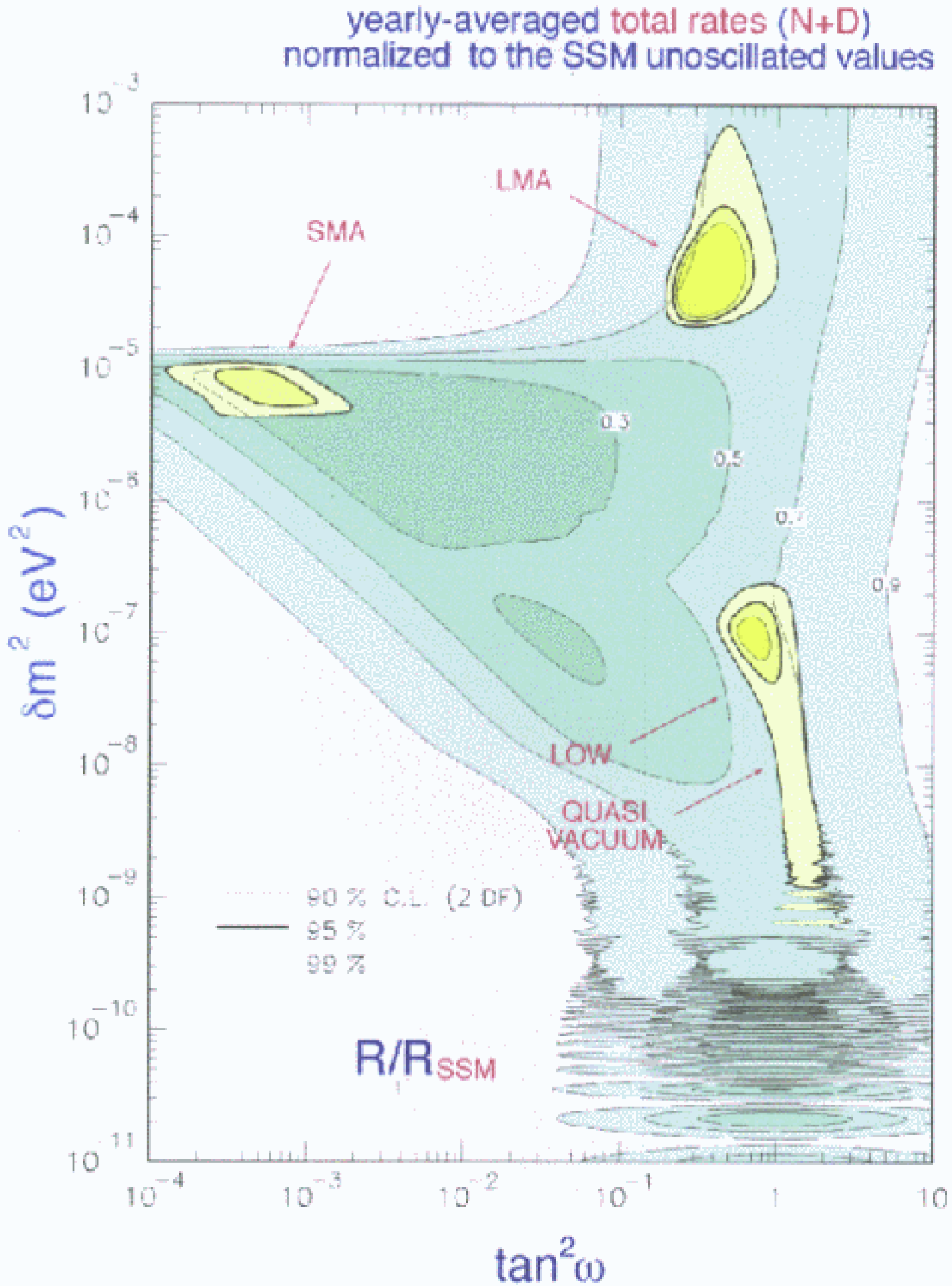


bimaximal mixing $\longrightarrow$ $\begin{cases} s^2_\omega = s^2_\psi = \frac{1}{2} \\ s^2_\varphi = 0 \end{cases}$

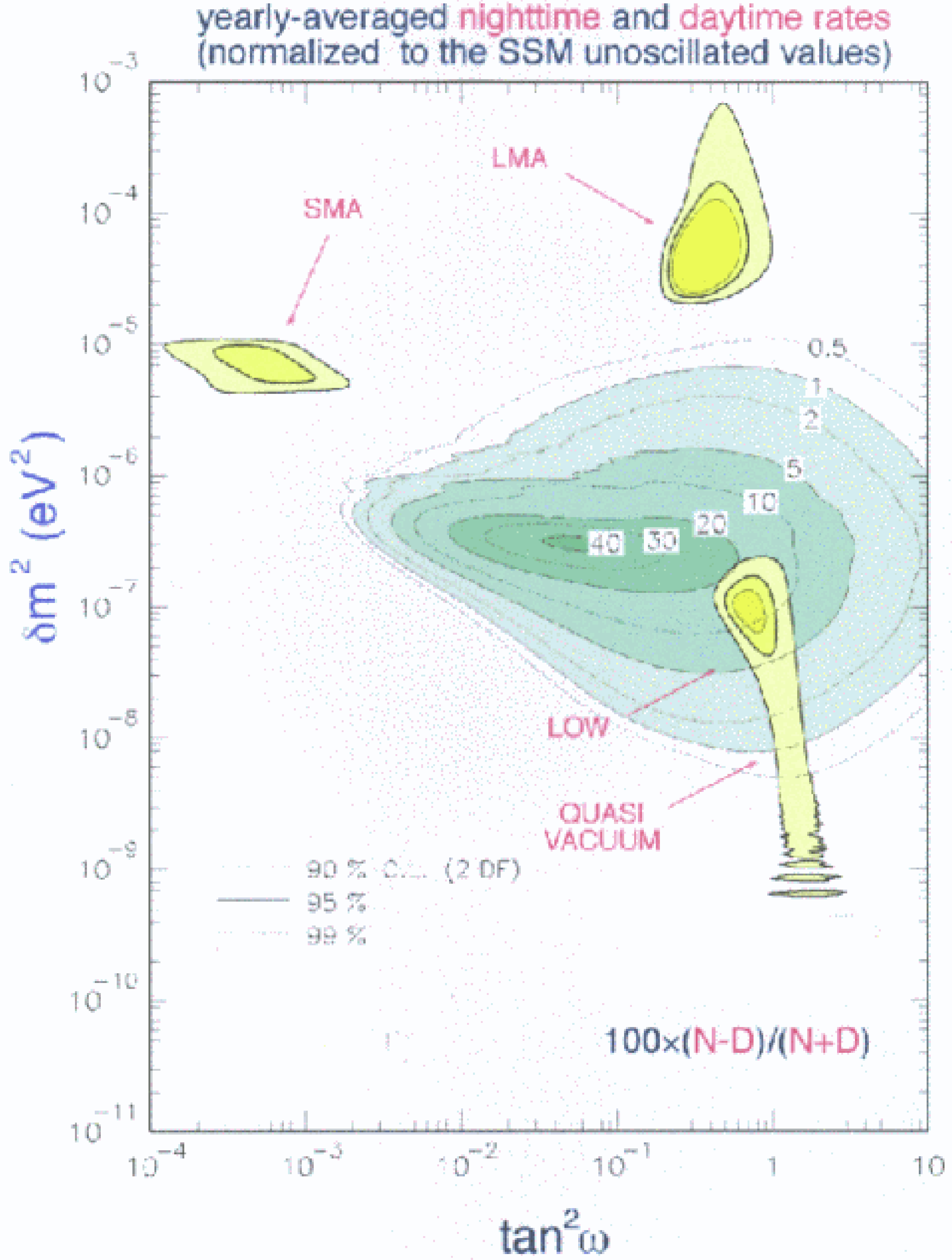


bimaximal mixing at small φ $\longrightarrow$ $\begin{cases} s^2_\omega = s^2_\psi = \frac{1}{2} \\ s^2_\varphi \sim \text{few percent} \end{cases}$

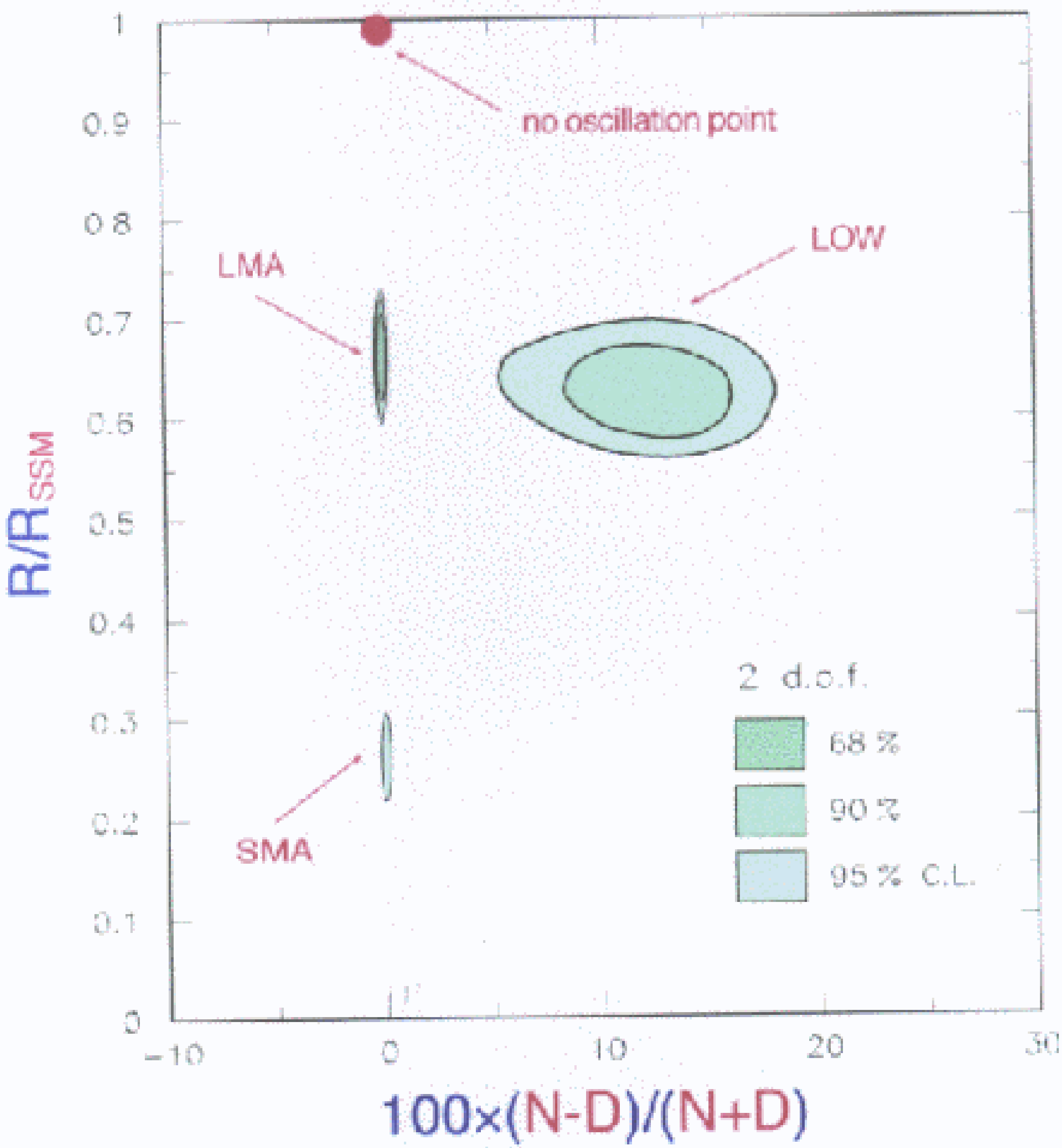
Borexino total rates compared with the SMA, LMA and LOW solutions



Borexino N-D asymmetry compared with the SMA, LMA and LOW solutions

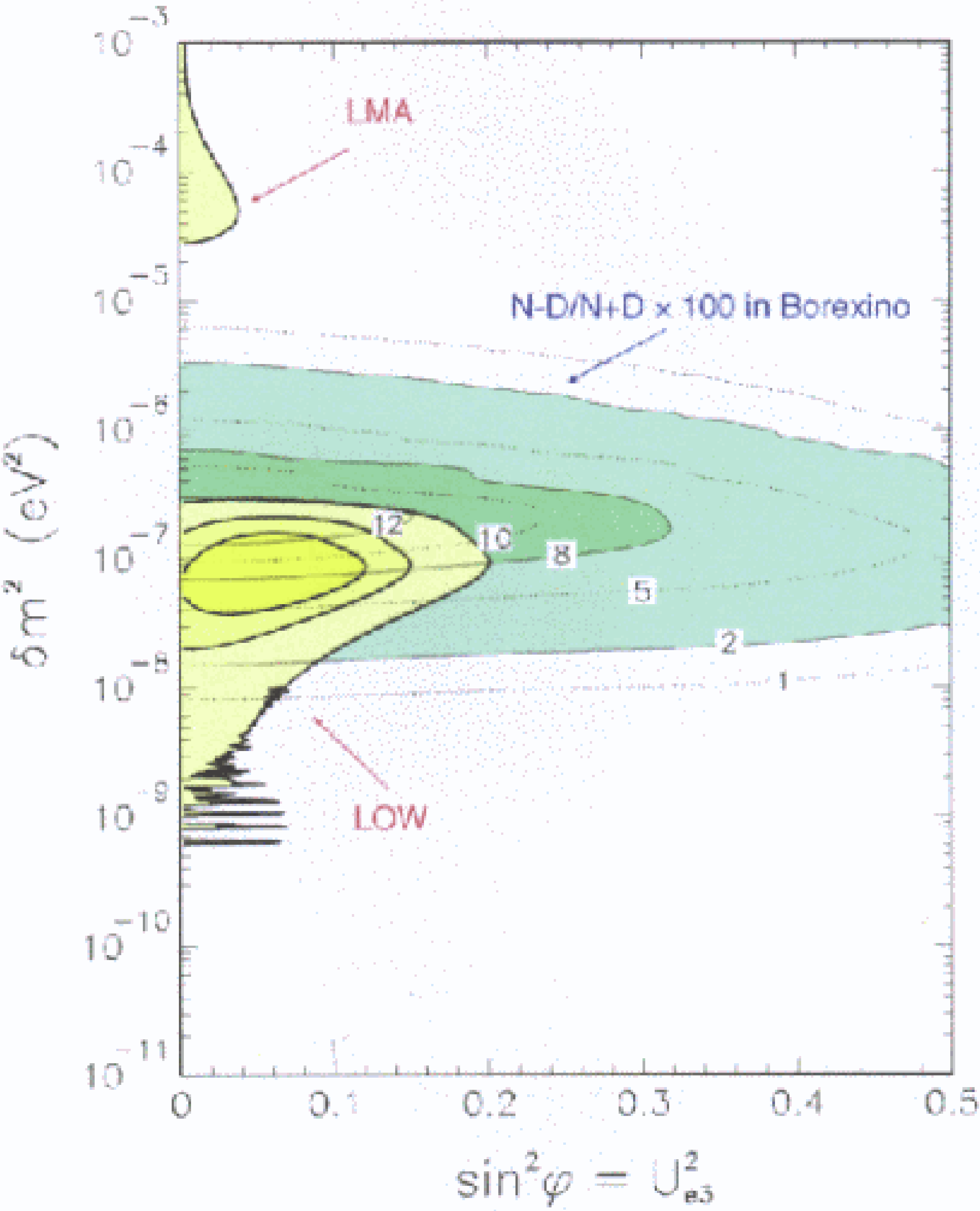


Borexino discovery potential compared with the SMA, LMA and LOW solutions



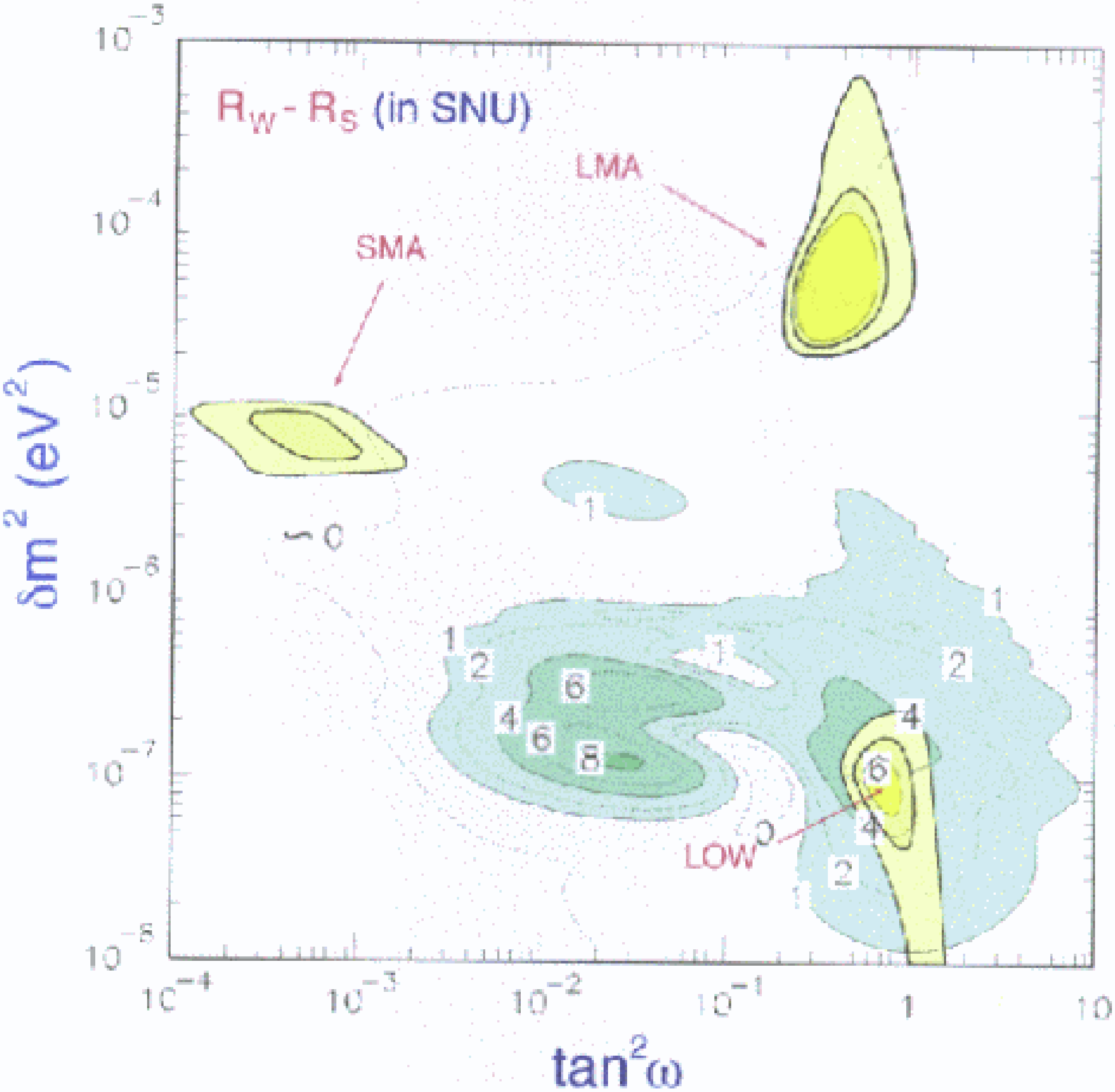
Borexino N-D asymmetry compared with the LMA and LOW solutions at maximal mixing ($\omega = \pi/4$)

yearly-averaged nighttime and daytime rates
(normalized to the SSM unoscillated values)



Gallium Neutrino Observatory

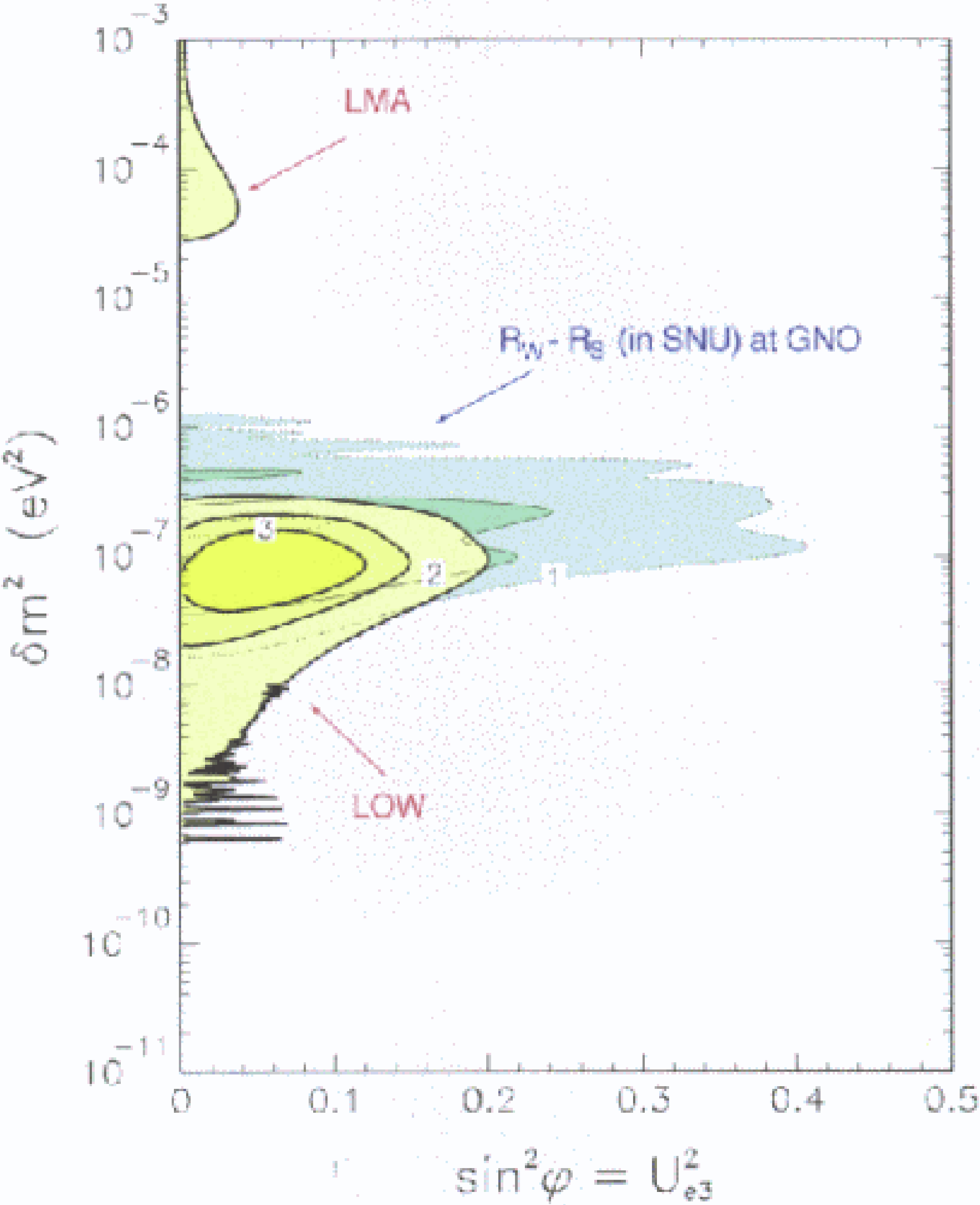
potential discovery of GNO compared with the SMA, LMA and LOW solutions



- expected gallium absorption rates (in SNU) averaged over "winter" and "summer" (eccentricity effects removed)
- MSW-induced seasonal variations of the order ~4-6 SNU are expected in a Ga experiment within the LOW solution (mainly from pp neutrinos)
- such variations might well be observed at GNO, the expected statistical error after one solar cycle being ~2 SNU (or less)

Gallium Neutrino Observatory

Comparison with the LMA and LOW solutions at maximal mixing ($\omega = \pi/4$)



- expected gallium absorption rates (in SNU) averaged over "winter" and "summer" (eccentricity effects removed)
- MSW-induced seasonal variations of the order ~4-6 SNU are expected in a Ga experiment within the LOW solution (mainly from pp neutrinos)
- such variations might well be observed at GNO, the expected statistical error after one solar cycle being ~2 SNU (or less)

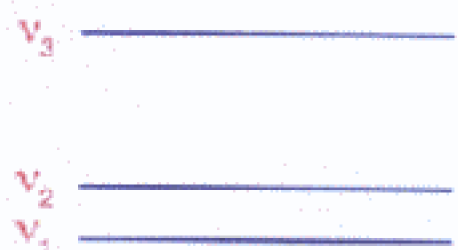
Beyond the "one dominant mass scale approximation"

⇓

CHOOZ limits to the solar neutrino problem

① CHOOZ excludes large ν_e mixing between any two states separated by $\Delta m^2 \geq 10^{-3}\ eV^2$

② so, concerning m^2



since $m^2 \geq 10^{-3}\ eV^2$
(from atmospheric ν data)

⇓

ν_3 must have small mixing with ν_e ⇒ small $<\nu_3|\nu_e> = U_{e3} = s_\varphi$

③ and concerning δm^2

either ν_1 or ν_2 or both must be mixed with ν_e
(from solar ν data)

⇓

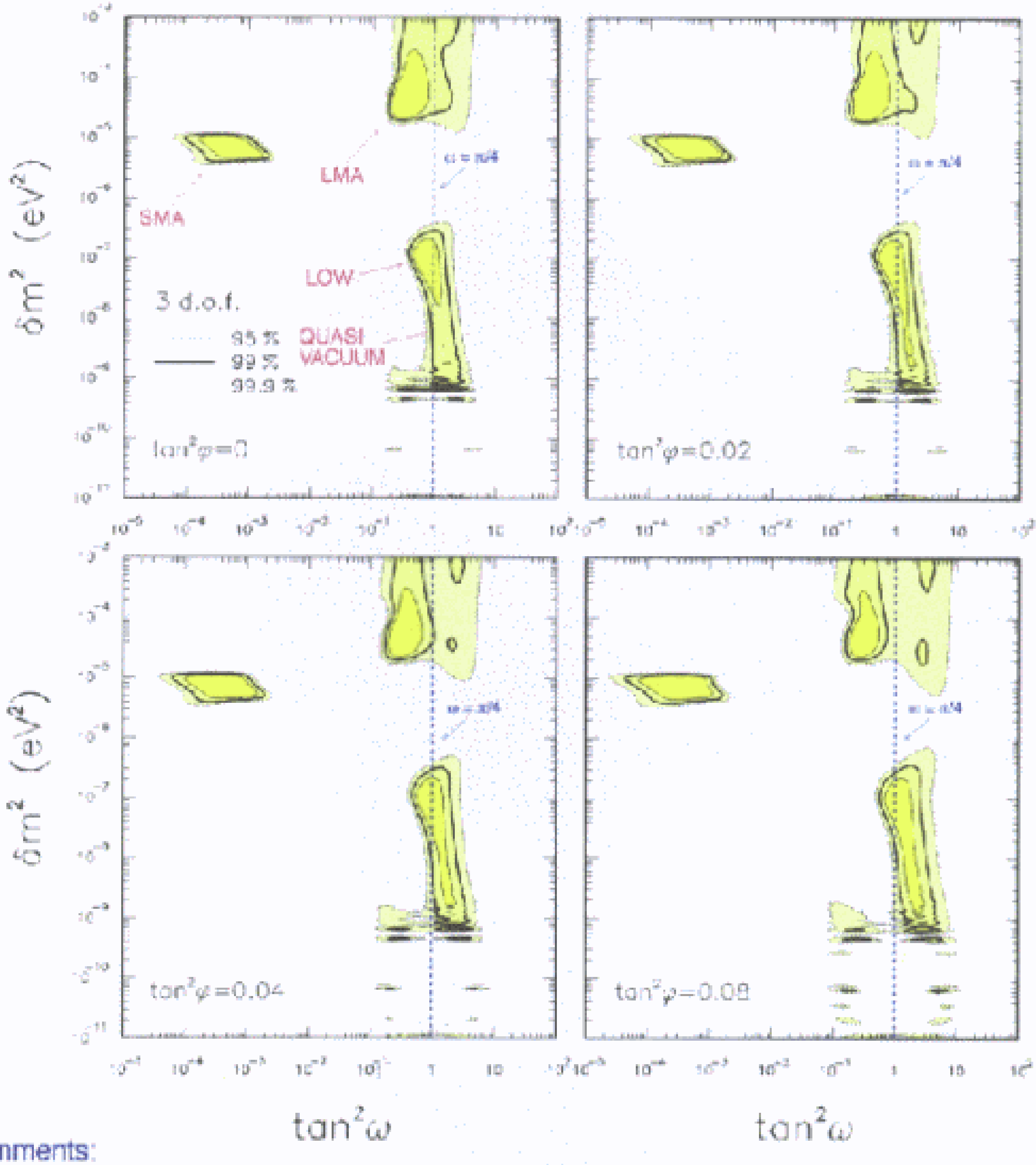
δm^2 must be smaller than $\sim 10^{-3}\ eV^2$

CHOOZ puts upper limits on

- $\sin^2\varphi$ (≤ few %)
- δm^2 ($\leq 10^{-3}\ eV^2$)

3ν solar solutions for finite m^2 ($m^2 = 1.5 \times 10^{-3}\,eV^2$)

total rates with constraints from Sp(D)+Sp(N)

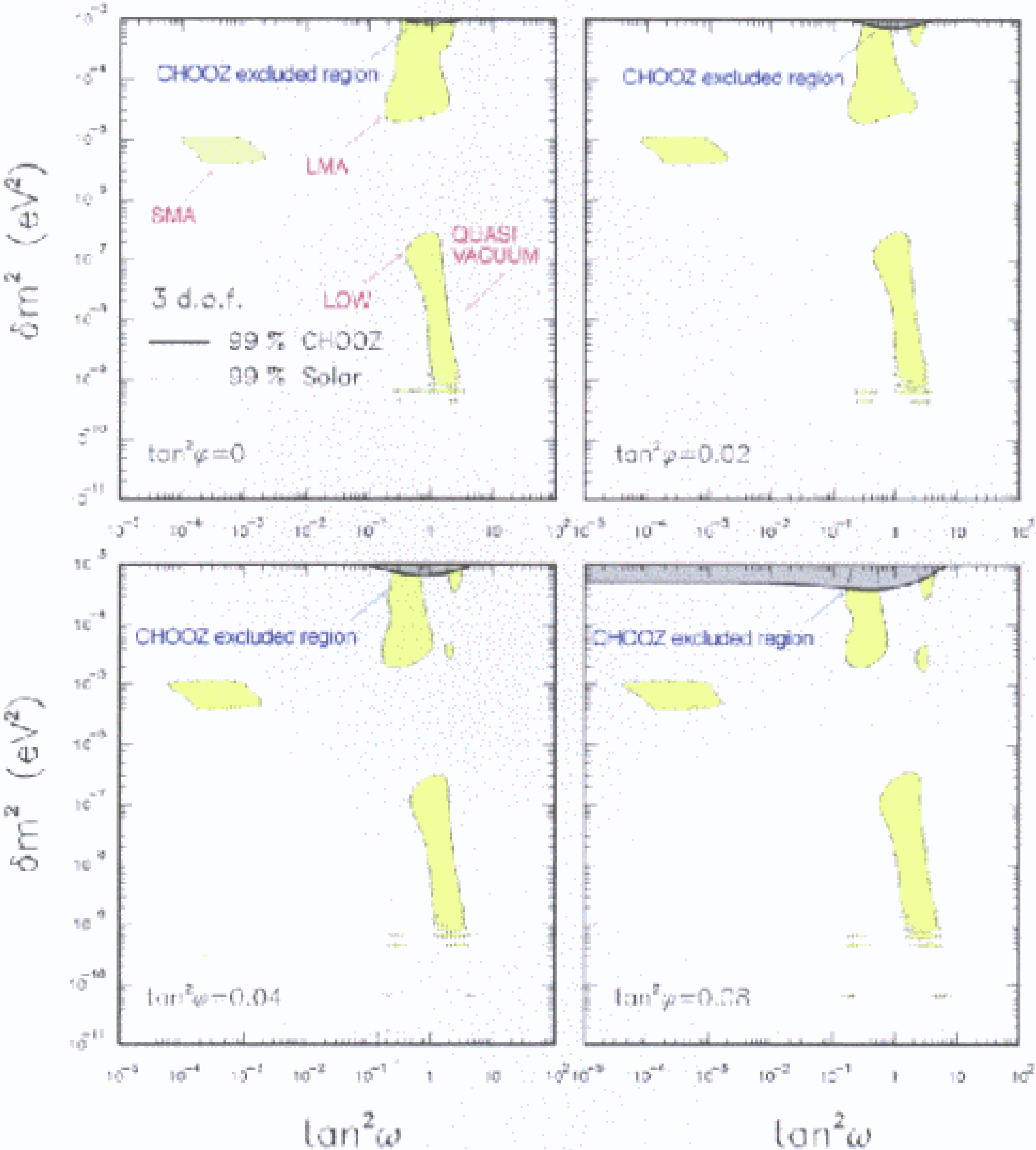


Comments:

- Removal of the $m^2 = \infty$ approximation in the solar ν analysis would not practically change the solar ν solutions
- In particular, no upper bound on δm^2 at 99% C.L. from solar ν data alone

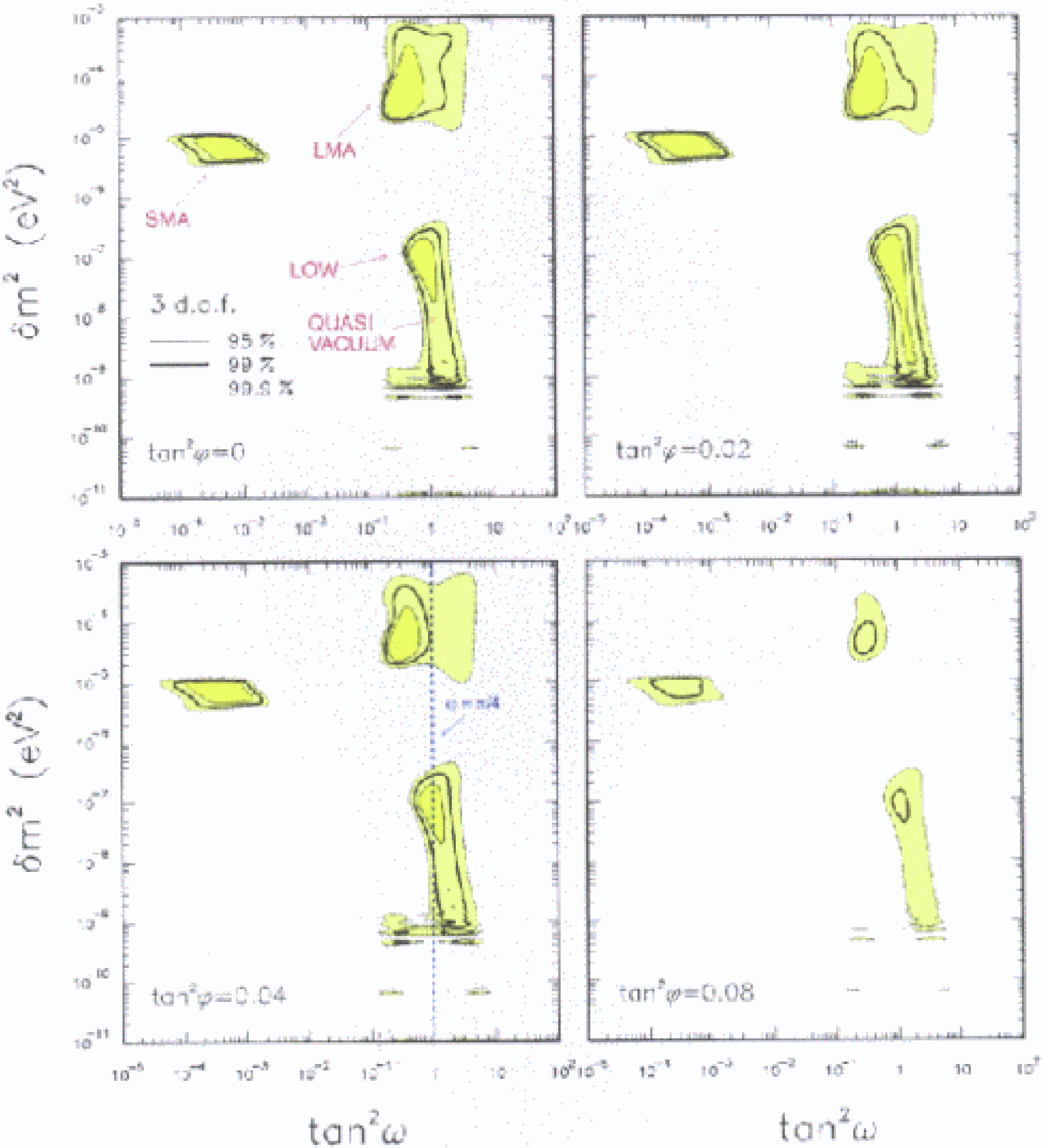
CHOOZ excluded region compared with the 3ν solar solutions

$(m^2 = 1.5 \times 10^{-3} eV^2)$



solar + CHOOZ data

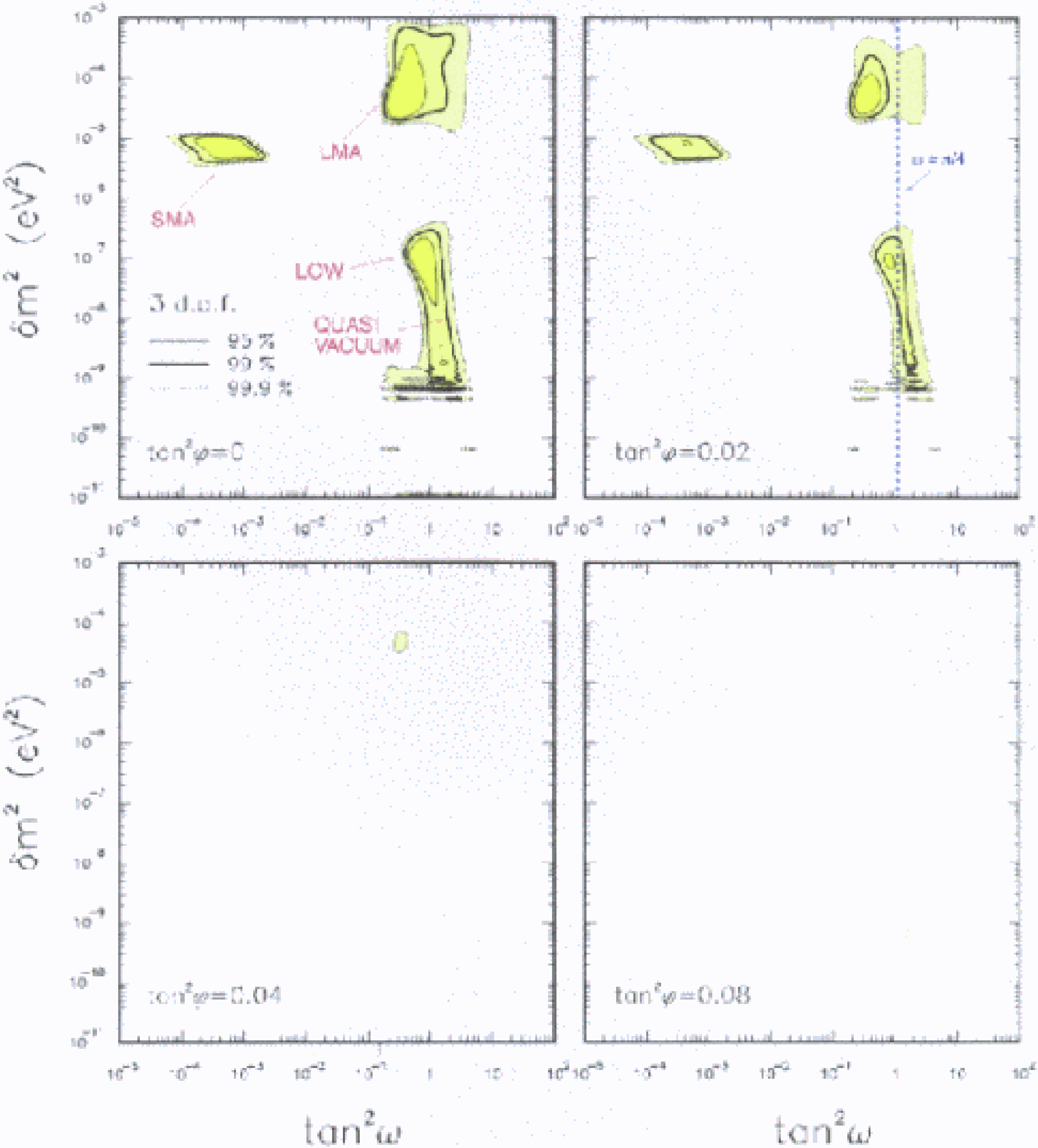
$(m^2 = 1.5 \times 10^{-3} eV^2)$



⟹ Strong constraints on both δm^2 and $\tan^2\varphi$ when solar + CHOOZ data are taken into account!

solar + CHOOZ data

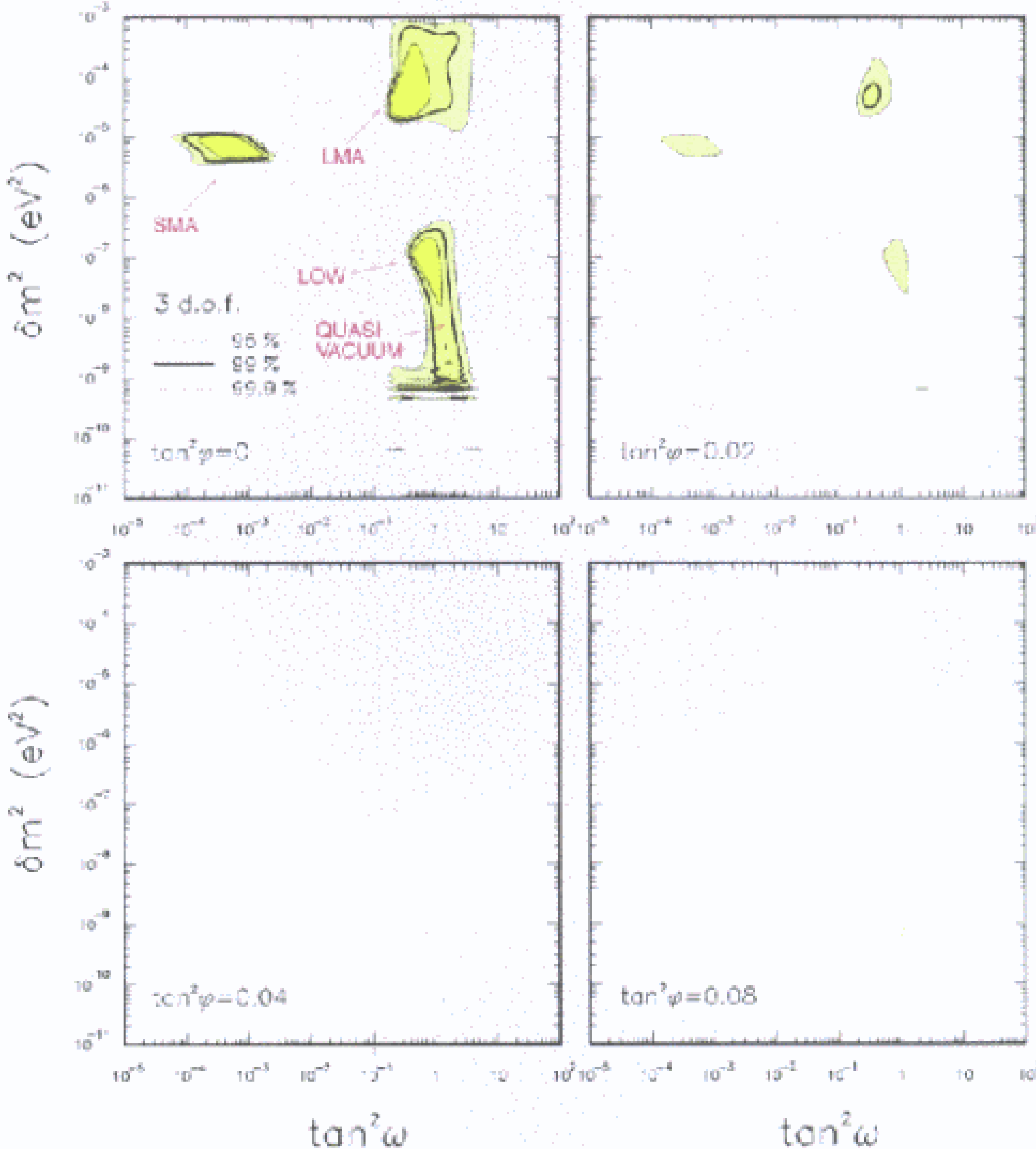
($m^2 = 3.0 \times 10^{-3}\,eV^2$)



⟹ More stringent constraints on $\tan^2\varphi$ for increasing m^2

solar + CHOOZ data

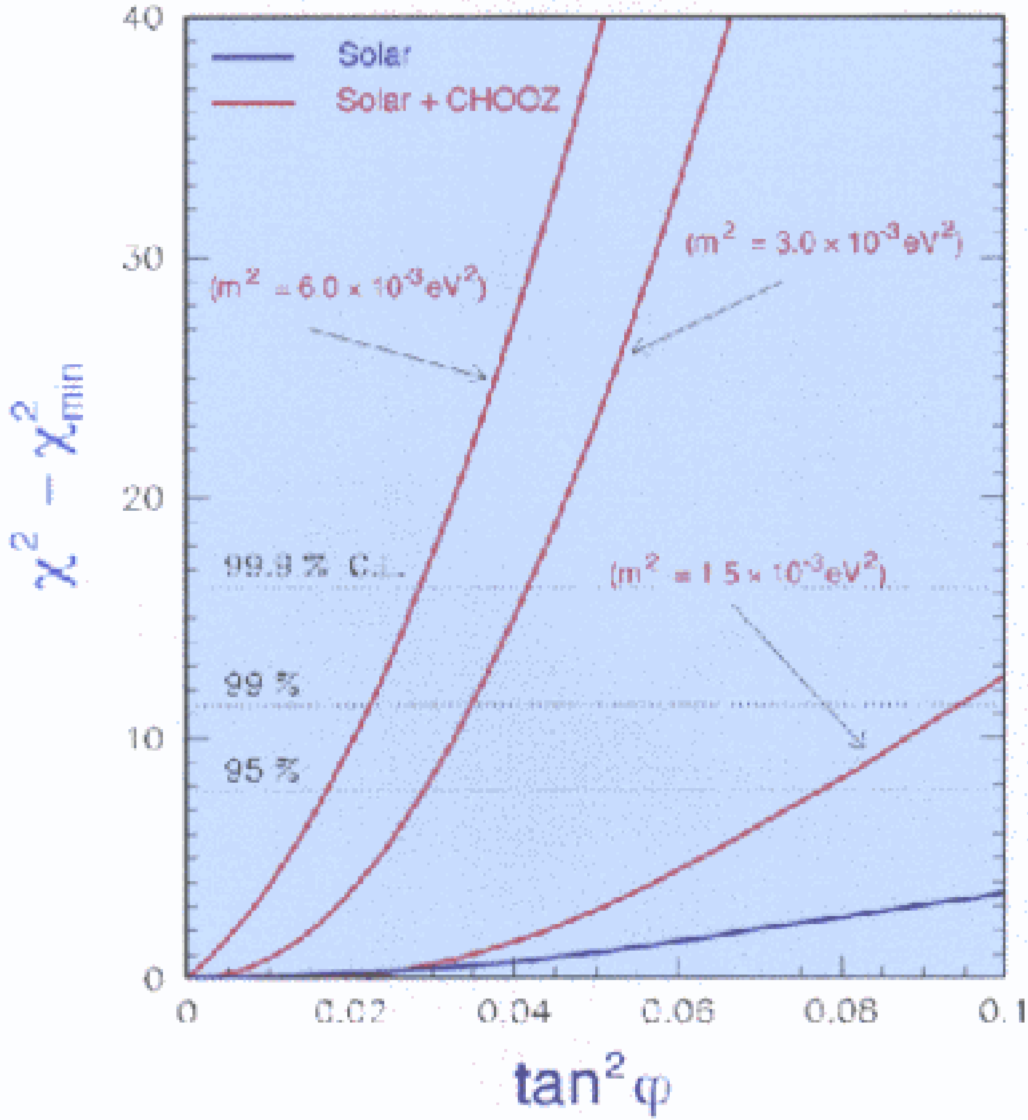
($m^2 = 6.0 \times 10^{-3}\,eV^2$)



⇒ The solar solutions in the limit $\varphi = 0$ are independent of m^2 (they correspond to a pure 2ν case)

solar + CHOOZ data

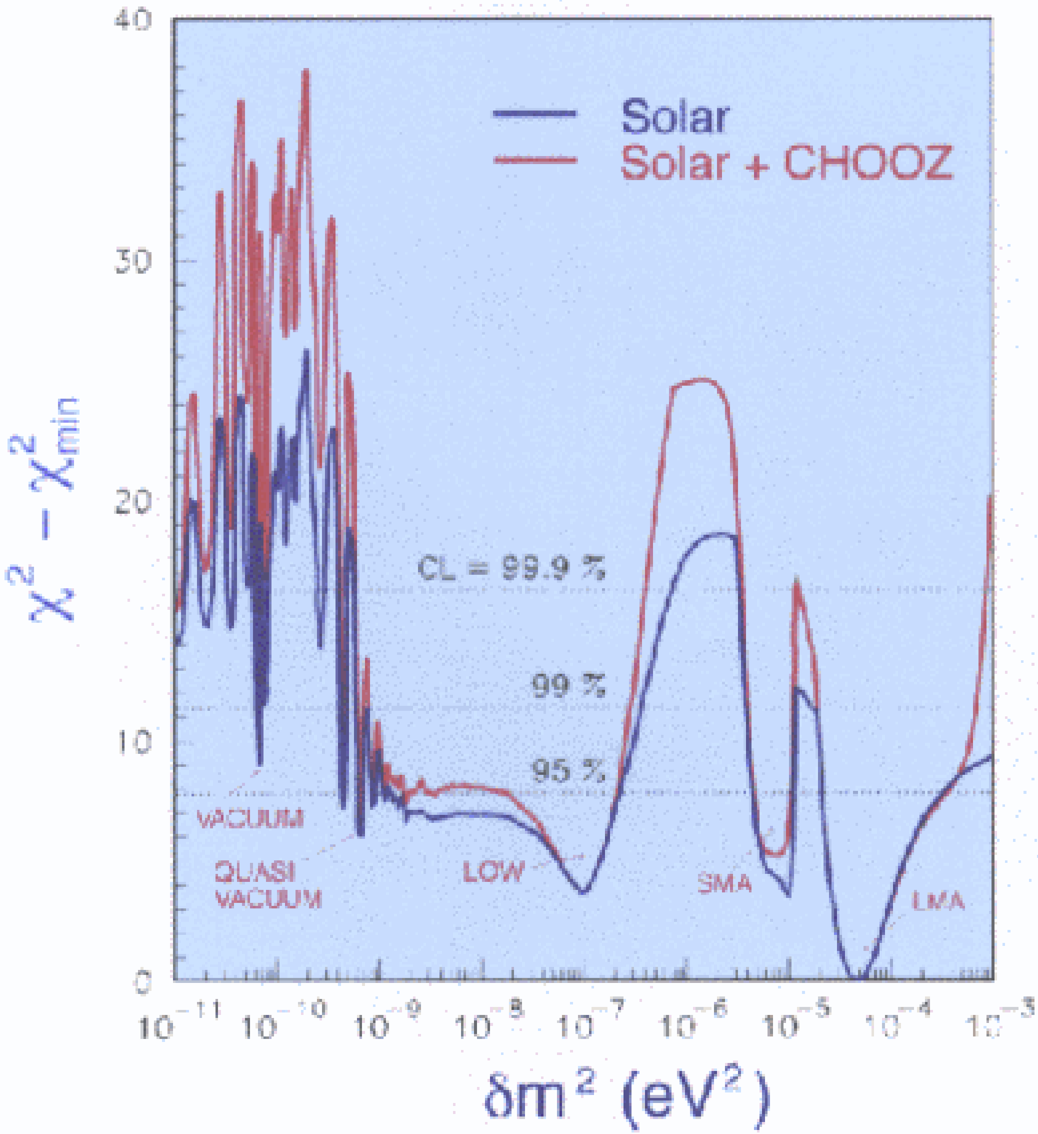
χ^2 behaviour for different values of m^2



- Strong constraints on $\tan^2\varphi$ when solar + CHOOZ data are taken into account
- More stringent constraints on $\tan^2\varphi$ for increasing m^2

solar + CHOOZ data

χ^2 behaviour in terms of of δm^2 ($\tan^2\varphi$ unconstrained)



- More stringent constraints on δm^2 from solar + CHOOZ data

Summary on solar ν (in 6 points)

① Still multiplicity of solar neutrino solutions:

MSW: LMA preferred, LOW promising, SMA less favored
VAC: serious problems for VAC, but interest for quasi-VAC (in the range $10^{-8} \div 10^{-9}$ eV^2)

② The LOW solution is acceptable and can provide

maximal $\nu_1 \leftrightarrow \nu_2$ mixing ($\omega = \pi/4$) for nonzero φ

③ Bounds on φ from solar ν data alone are loose (even more than for atmospheric data). However, their preference for

$$s^2_\varphi \sim 0$$

is a good sign of consistency with CHOOZ.

④ CHOOZ provides upper bounds on s^2_φ and δm^2

⑤ Unambiguous selection of ONE solution will not be possible in SK for several years. Much higher statistics needed (e.g., in the spectrum).

⑥ We absolutely need more solar ν data ! Eagerly waiting for SNO, GNO, Borexino results ..., as well as for direct tests of LMA with KAMLAND, to improve discrimination of solar ν solutions.

3ν summary

Within the "standard" 3ν interpretation of neutrino oscillation data, we have a lot of experiments or projects constraining the neutrino parameters:

masses		mixing	
δm^2	U^2_{e1}	U^2_{e2}	U^2_{e3}
	$U^2_{\mu 1}$	$U^2_{\mu 2}$	$U^2_{\mu 3}$
m^2	$U^2_{\tau 1}$	$U^2_{\tau 2}$	$U^2_{\tau 3}$

(blue) probed by solar neutrino experiments

(yellow) probed by "terrestrial" neutrino experiments

- At present, most stable constraints on m^2 and $U^2_{\mu 3}$, $U^2_{\tau 3}$.
- CHOOZ tells us that U^2_{e3} must be small, and atmospheric and solar data also prefer small φ, but there is no reason for it to be zero !
- Constraints on δm^2, U^2_{e1} , U^2_{e2} depend on which solar solution is picked up.
- CHOOZ + solar data ⟶ upper bound on δm^2
- Most important tasks for the next years:
  - ⟹ measure or constrain further U^2_{e3} (reactors & LBL)
  - ⟹ reduce the multiplicity of solar ν solutions
  - ⟹ check and (dis)prove non-standard interpretations